NEW

Artemis | DART | James Webb Space Telescope | Lucy | And more

ALL ABOUT SPACE™ Annual

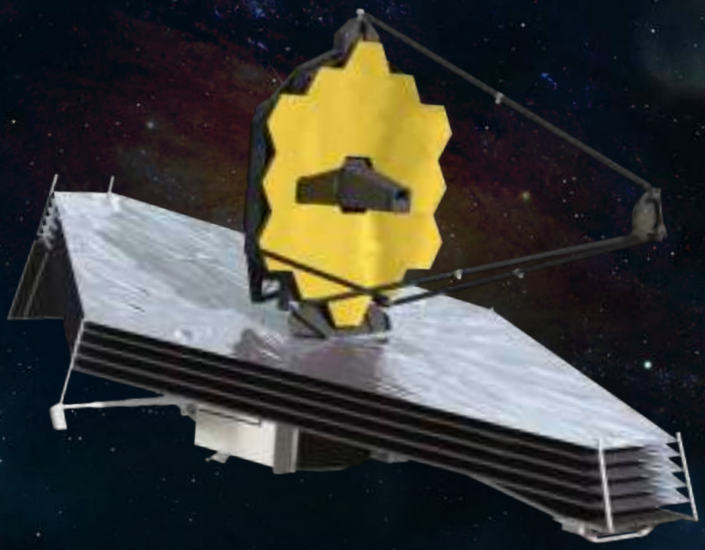


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FUTURE

TENTH EDITION

Everything you want to know about our galaxy and beyond



ALL ABOUT SPACE Annual

The past couple of years saw space exploration slow down a bit for obvious reasons, but it came back with a (big) bang in 2022. The James Webb Space Telescope showed us distant wonders of the universe in more detail than ever before, it looks like DART proved its asteroid-deflecting hypothesis (although all the data is still to come in over the next couple of years), and at the time of going to press, Artemis 1 was gearing up for its delayed launch. If the first unmanned mission in NASA's new moonshot program goes to plan, then we could see astronauts walk on the lunar surface again by 2025. You'll find all of these missions and more in this year's **All About Space Annual**, plus the latest deep space discoveries and space science research that are pushing our understanding of the cosmos further than ever before.

FUTURE

ALL ABOUT SPACE Annual

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Cover images
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Advertising
Media packs are available on request
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Printed by William Gibbons, 26 Planetary Road, Willenhall, West Midlands, WV13 3XT

Distributed by Marketforce, 5 Churchill Place, Canary Wharf, London, E14 5HU
www.marketforce.co.uk Tel: 0203 787 9001

All About Space Annual Volume 10 (ASB4912)

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© NASA; Getty

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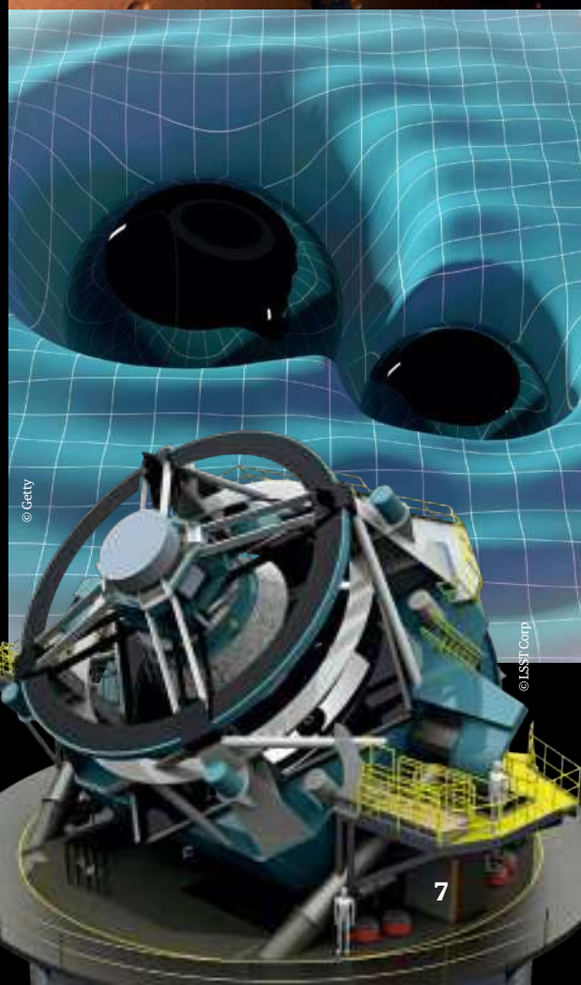
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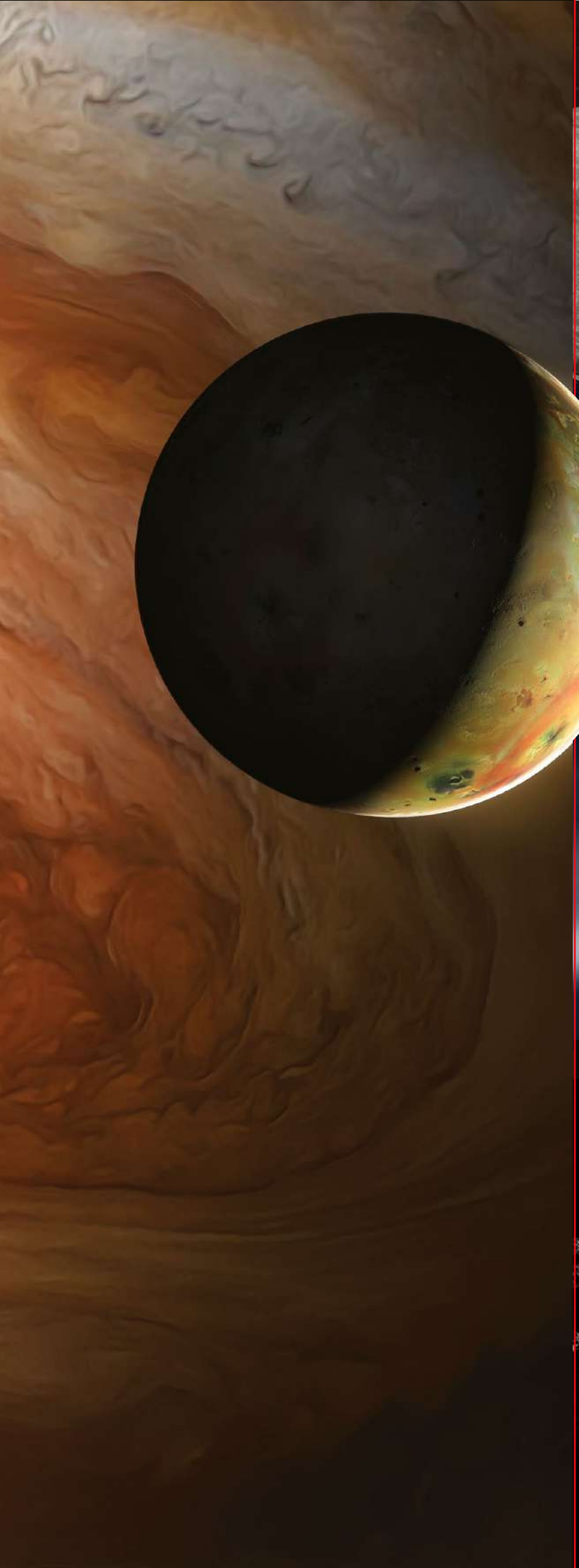
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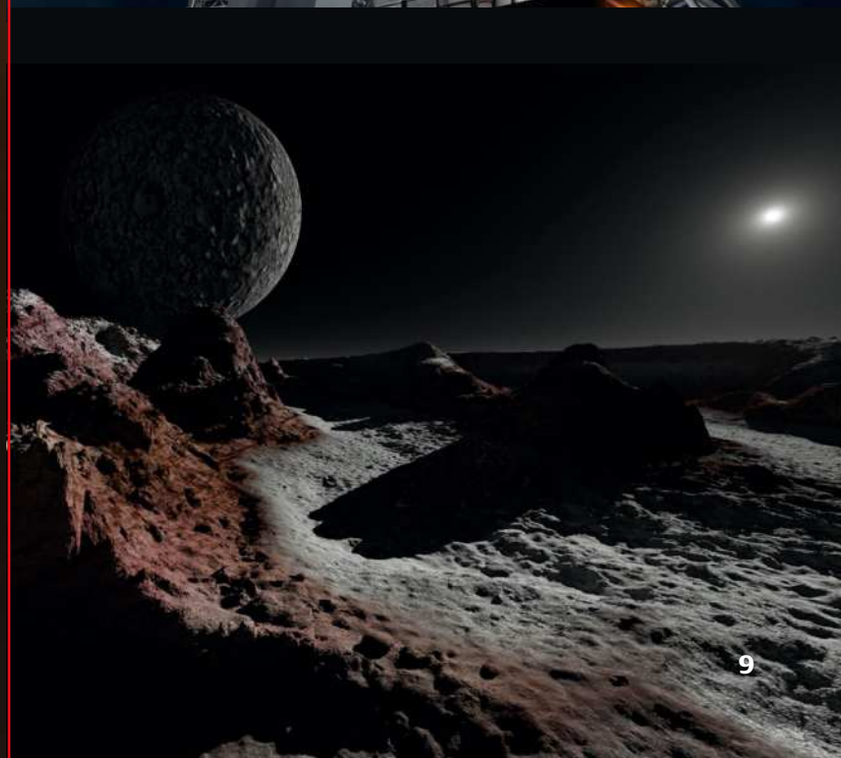
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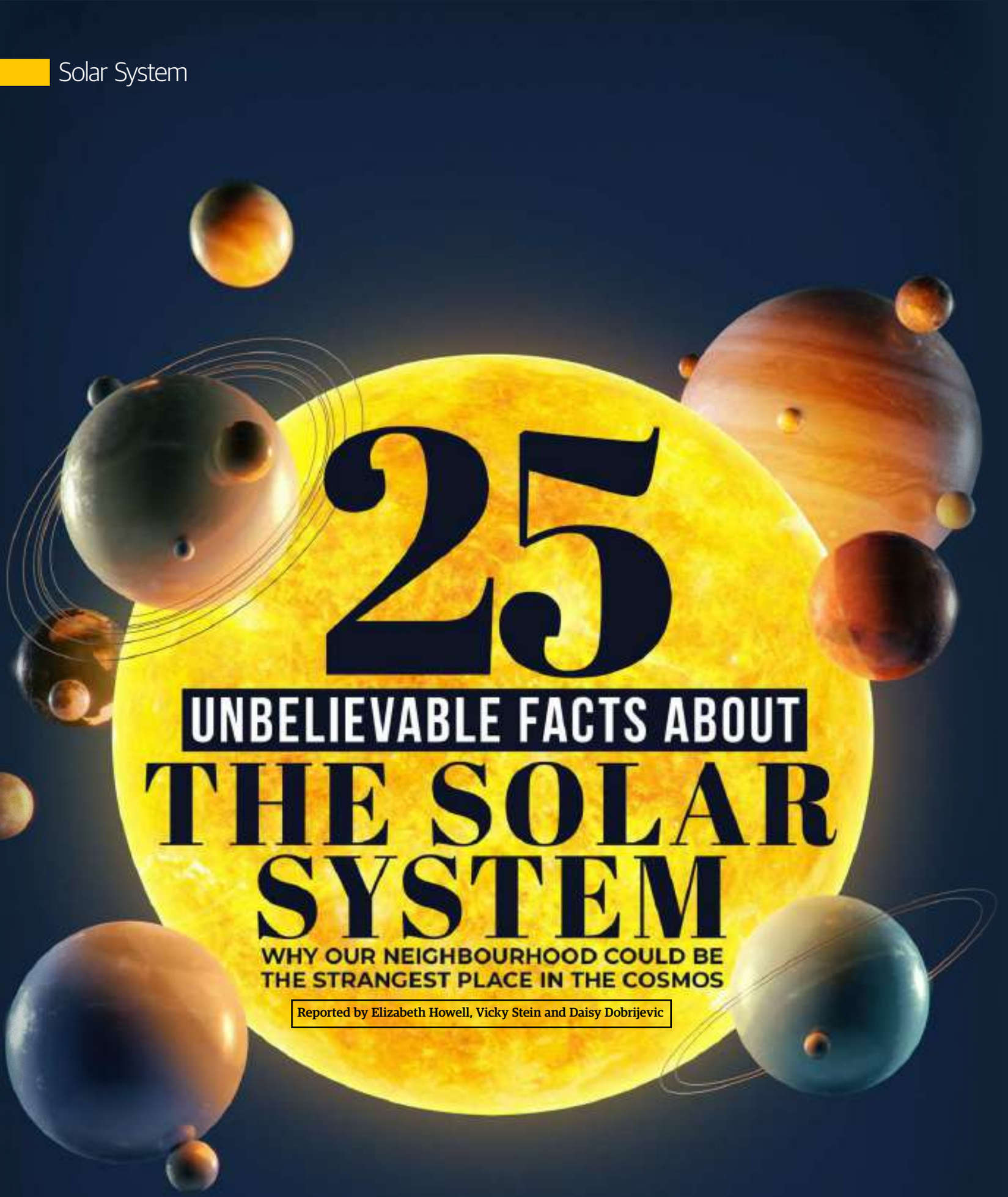
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25 UNBELIEVABLE FACTS ABOUT THE SOLAR SYSTEM

WHY OUR NEIGHBOURHOOD COULD BE THE STRANGEST PLACE IN THE COSMOS

Reported by Elizabeth Howell, Vicky Stein and Daisy Dobrijevic

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1 THE SOLAR SYSTEM IS REALLY BIG

NASA's Voyager 1 spacecraft was launched in 1977. More than three decades later, in 2012 it became the first human-made object to enter interstellar space by crossing the heliopause – the edge of the heliosphere. That's the boundary beyond which most of the Sun's ejected particles and magnetic fields dissipate. "If we define our Solar System as the Sun and everything that primarily orbits the Sun, Voyager 1 will remain within the confines of the Solar System until it emerges from the Oort Cloud in another 14,000 to 28,000 years," NASA says.

"THE MOON IS BOTH MIND-BOGGLINGLY DISTANT AND INCREDIBLY CLOSE DEPENDING ON HOW YOU THINK ABOUT IT"

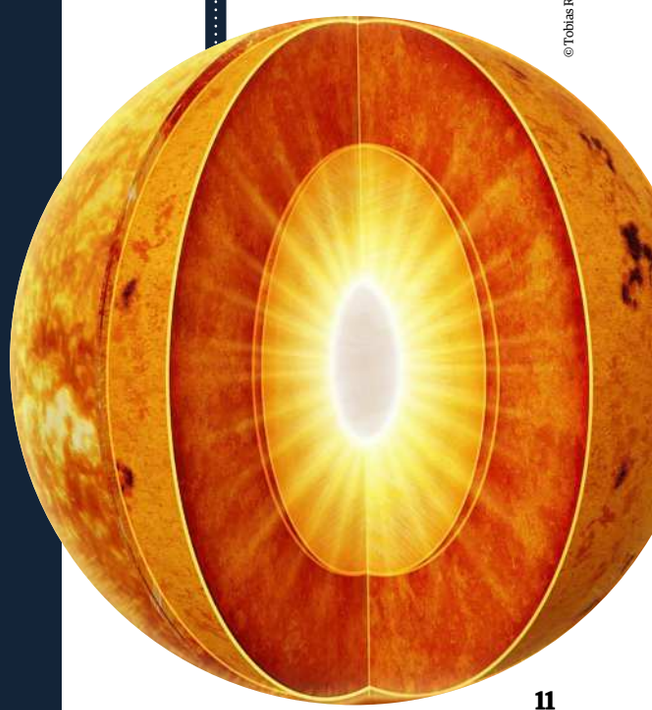
2 EVEN JUST OUR NEIGHBOURHOOD IS REALLY BIG

Depending on how carefully you do the calculations and how you arrange them, all of the planets in the Solar System could fit in between Earth and its Moon. The distance between Earth and the Moon varies as it orbits around us, as does the diameter of each of the planets – they're wider at their equators, so Saturn and Jupiter would have to be tilted sideways for this to work. But imagine lining them all up, pole to pole. They'd just barely squeeze in between us and our closest companion in space, blocking out the sky with their rings and gas giant bulk as they did so.

The Moon is the farthest from Earth we've ever sent humans, and it's both mind-bogglingly distant and incredibly close depending on how you think about it. Eight enormous planets could fit between here and there, and the distance from Earth to the Sun is more than 390 times the distance from Earth to the Moon. Scientists use an approximation of the Earth-Sun distance, also known as one astronomical unit, or AU, to compare distances within the Solar System. Jupiter is about 5.2 AU from the Sun, and Neptune is 30.07 AU from the Sun – around 30 times as far from the star as Earth.

3 THE SUN'S ATMOSPHERE IS HOTTER THAN ITS SURFACE

While the Sun's visible surface, the photosphere, is 5,500 degrees Celsius (10,000 degrees Fahrenheit), its upper atmosphere has temperatures in the millions of degrees. It's a large temperature differential with little explanation. NASA has several Sun-gazing spacecraft on the case, however, and they have some ideas for how the heat is generated. One is 'heat bombs', which happen when magnetic fields cross and realign in the corona. Another is when plasma waves move from the Sun's surface into the corona. With new data from the Parker Solar Probe – which recently became the first human-made object to 'touch' the Sun – coming in all the time, we're closer than ever to unlocking the mysteries at the heart of our Solar System.



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4 MERCURY IS STILL SHRINKING

Mercury is already the smallest planet in the Solar System, and is the second-densest after Earth. And it's only getting smaller and denser. For many years, scientists believed that Earth was the only tectonically active planet in the Solar System. But that changed after the Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) spacecraft did the first orbital mission at Mercury, mapping the entire planet in high definition and getting a look at the features on its cratered surface.

In 2016, data from MESSENGER revealed cliff-like landforms known as fault scarps. Because the fault scarps are relatively small, scientists can be sure that they weren't created that long ago and that the small planet is still contracting 4.5 billion years after the Solar System was formed.


© Getty

5 VENUS IS SWEPT BY POWERFUL WINDS THAT COULD HARBOUR LIFE

Venus is a hellish planet with a high-temperature, high-pressure environment on its surface. Bone-dry and hot enough to melt lead, it's not exactly a welcoming environment, and has probably always been inhospitable to life. When the heavily shielded Venera spacecraft from the Soviet Union landed there in the 1970s, each lasted a few minutes, or at most a few hours, before melting or being crushed beyond their ability to function.

But even above its surface, the planet has a bizarre environment. Scientists have found that its upper winds flow 50 times faster than the planet's rotation. The European Venus Express spacecraft, which orbited the planet between 2006 and 2015, tracked the winds over long periods and detected periodic variations. It also found that the hurricane-force winds appeared to be getting stronger over time. A 2020 study that thrilled many astrobiologists detected phosphine, a possible sign of decaying biological matter, high in the Venusian clouds. Could they be a sign of life? Not without sufficient water, claim follow-up studies that firmly reject the possibility of life in Venus' dry and windy atmosphere.

6 EARTH'S VAN ALLEN BELTS ARE MORE BIZARRE THAN EXPECTED

There are several bands of magnetically trapped, highly energetic charged particles surrounding our planet, known as the Van Allen belts, named after the discoverer of the phenomenon. While we've known about the belts since the dawn of the Space Age, the Van Allen Probes, launched in 2012, have provided our best ever view of them. They've uncovered quite a few surprises along the way. We now know that the belts expand and contract according to solar activity. Sometimes the belts are very distinct from one another, and sometimes they swell into one massive unit. An extra radiation belt beyond the known two was spotted in 2013. Understanding these belts helps scientists make better predictions about space weather or solar storms.

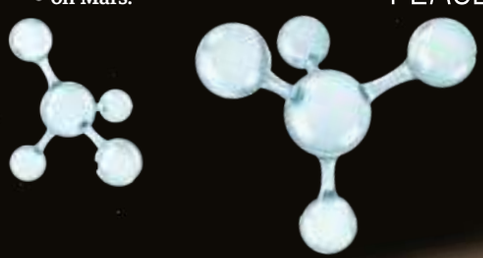

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7 ORGANIC MOLECULES ARE EVERYWHERE

Organics are complex carbon-based molecules found in living things, but can be created by non-biological processes too. While organic molecules are common on Earth, they can be found in many other places in the Solar System too. Scientists have found organics on the surface of Comet 67P/Churyumov-Gerasimenko, for example. The discovery bolstered the case that organic molecules on Earth could have been brought to the surface from space. Organics have also been found on the surface of Mercury, on Saturn's moon Titan - giving Titan its orange colour - and on Mars.

© Getty

"WHILE ORGANIC MOLECULES ARE COMMON ON EARTH, THEY CAN BE FOUND IN MANY OTHER PLACES TOO"



8 A VALLEY ON MARS COULD SWALLOW THE GRAND CANYON

At 4,000 kilometres (2,500 miles), the immense system of Martian canyons known as Valles Marineris is more than ten times as long as the Grand Canyon on Earth. Valles Marineris escaped the notice of earlier Mars spacecraft flying over other parts of the planet and was finally spotted by the global mapping mission Mariner 9 in 1971. And what a sight it was to miss - Valles Marineris could stretch from New York to Seattle. The lack of active plate tectonics on Mars makes it tough to figure out how the canyon formed. Some scientists think that a chain of volcanoes on the other side of the planet, known as Tharsis Ridge, which includes Olympus Mons, somehow bent the crust from the opposite side of Mars. That cataclysmic force activated cracks in the crust, vast amounts of subsurface water that emerged to carve away rock and glaciers that crunched new pathways into the canyon system.



© NASA

9 MARS' BIGGEST VOLCANO IS BIGGER THAN HAWAII

While Mars seems quiet now, gigantic volcanoes once dominated the surface of the planet. This includes Olympus Mons, the biggest volcano ever discovered in the Solar System. At 602 kilometres (374 miles) across, the volcano is comparable to the size of Arizona. It's 25 kilometres (16 miles) high, or triple the height of Mount Everest, the tallest mountain on Earth. By volume, Olympus Mons is 100 times larger than Earth's largest volcano, Hawaii's Mauna Loa. Scientists speculate that volcanoes on Mars can grow to such immense sizes because gravity there is much weaker than it is on Earth. In addition, while Earth's crust constantly moves, the Martian crust likely doesn't, although the debate among researchers continues. The Hawaiian islands were formed as a hotspot in the mantle created a chain of volcanoes in the crust cruising by above it, so if the surface of Mars isn't moving, a volcano could build up for longer in one spot.

© Getty

10 THE GREAT RED SPOT IS SHRINKING

Along with being the Solar System's largest planet, Jupiter also hosts the Solar System's largest storm. Known as the Great Red Spot, it's been observed in telescopes since the 1600s and studied by modern instruments like those on NASA's Juno, which recently provided evidence that the storm is hundreds of miles tall and likely fed by winds from thousands of miles below. The storm has been a raging conundrum for centuries, but in recent decades another mystery emerged: the spot is getting smaller. In 2014 the storm was only 16,500 kilometres (10,250 miles) across, about half its historic size. The shrinkage is being monitored in professional telescopes, and also by amateurs. Amateurs are often able to make more consistent measurements of Jupiter because viewing time on larger, professional telescopes is limited and often split between different objects.

11 JUPITER'S MOON IO HAS HUGE VOLCANIC ERUPTIONS

Compared to Earth's peaceful Moon, Jupiter's moon Io may come as a surprise. The Jovian moon has hundreds of volcanoes and is considered the most active moon in the Solar System, sending plumes of sulphur up to 300 kilometres (190 miles) into its atmosphere. As such, Io's volcanoes emit around one tonne of gases and particles into space near Jupiter each second. Io's eruptive nature is caused by the immense forces the moon is exposed to nestled in Jupiter's gravitational well, as well as its magnetic field. The moon's insides tense up and relax as it orbits closer to and farther from the planet, generating enough energy for volcanic activity. Scientists are still trying to figure out how heat spreads through Io's interior, though, making it difficult to predict where the volcanoes exist using scientific models alone.



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12 THERE IS WATER EVERYWHERE

Water was once considered rare in space. But water ice exists all over the Solar System. It's a common component of comets and asteroids. Water can be found as ice in permanently shadowed craters on Mercury and the Moon, though we don't know if there's enough to support prospective human colonies in those places. Mars also has ice at its poles, in frost and likely below the surface dust. Even smaller bodies in the Solar System have ice: Saturn's moon Enceladus and the dwarf planet Ceres, among others.

Scientists suspect Jupiter's moon Europa may be the most likely candidate for extraterrestrial life because against all expectations there's likely liquid water below its cracked and frozen surface. Europa, much smaller than Earth, may host a deep ocean that researchers suggest could contain twice as much water as all of Earth's oceans combined.

But we know that not all ice is the same. A close-up examination of Comet 67P by the European Space Agency's Rosetta spacecraft revealed a different kind of water ice than the kind found on Earth.



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13 SATURN HAS A YIN-YANG MOON

Iapetus has a very dark hemisphere that always faces away from the planet and a very light hemisphere that always faces towards Saturn. Most asteroids, moons and planets are relatively uniform across their surfaces, but Iapetus sometimes shines brightly enough to be spotted by telescopes and then dims down by several magnitudes when oriented in the other direction. Current research suggests that Iapetus is made mostly of water ice. As the moon's darker side faces the Sun, scientists hypothesise, water ice sublimates away from that area, leaving darker rock behind. That may have created a positive feedback loop, as dark material heats up more than bright, reflective ice – as the darker, warmer side of the moon loses its ice, it becomes easier to heat up each time it faces the Sun, hastening the loss of more ice.

14 TITAN HAS A LIQUID CYCLE

Another weird moon in Saturn's system is Titan, which hosts a liquid 'cycle' that moves material between the atmosphere and the surface. That sounds a lot like Earth's water cycle, but Titan's immense lakes are filled with liquid methane and ethane, possibly over a layer of water. Researchers hope to use data from the Cassini-Huygens mission to tease out some of Titan's secrets before designing a submarine that might one day plumb the depths of the mysterious moon.

15 SATURN HAS A HEXAGONAL STORM

Saturn's northern hemisphere features a raging six-sided storm nicknamed 'the hexagon'. This hexagon, a towering, multilayered storm, has been present on the ringed planet for decades, if not hundreds of years. The strange storm was discovered in the 1980s, but was barely visible until the Cassini mission flew by between 2004 and 2017. Images and data from Cassini reveal the storm to be 300 kilometres (180 miles) tall, 32,000 kilometres (20,000 miles) wide and composed of air moving at about 320 kilometres (200 miles) per hour.

16 RINGS ARE MORE COMMON THAN WE THOUGHT

We've known about Saturn's rings since telescopes were invented in the 1600s, but it took spacecraft and more powerful telescopes built in the last 50 years to reveal more. We now know that every planet in the outer Solar System – Jupiter, Saturn, Uranus and Neptune – has a ring system. But the rings differ from planet to planet: Saturn's spectacular halo, made in part of sparkly, reflective water ice, is not repeated anywhere else. Instead the rings of the other giants are likely made of rocky particles and dust. Rings aren't limited to planets, either. In 2014 astronomers discovered rings around the asteroid 10199 Chariklo.

17

SPACECRAFT HAVE VISITED EVERY PLANET

We've been exploring space for more than 60 years, and have been lucky enough to get close-up pictures of dozens of celestial objects. Most notably, we've sent spacecraft to all of the planets in our Solar System – Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune – as well as two dwarf planets, Pluto and Ceres. The bulk of the flybys came from NASA's Voyager 1 and Voyager 2, which left Earth more than four decades ago and are still transmitting data from interstellar space. Between them the Voyagers clocked visits to Jupiter, Saturn, Uranus and Neptune thanks to an opportune alignment of the outer planets.

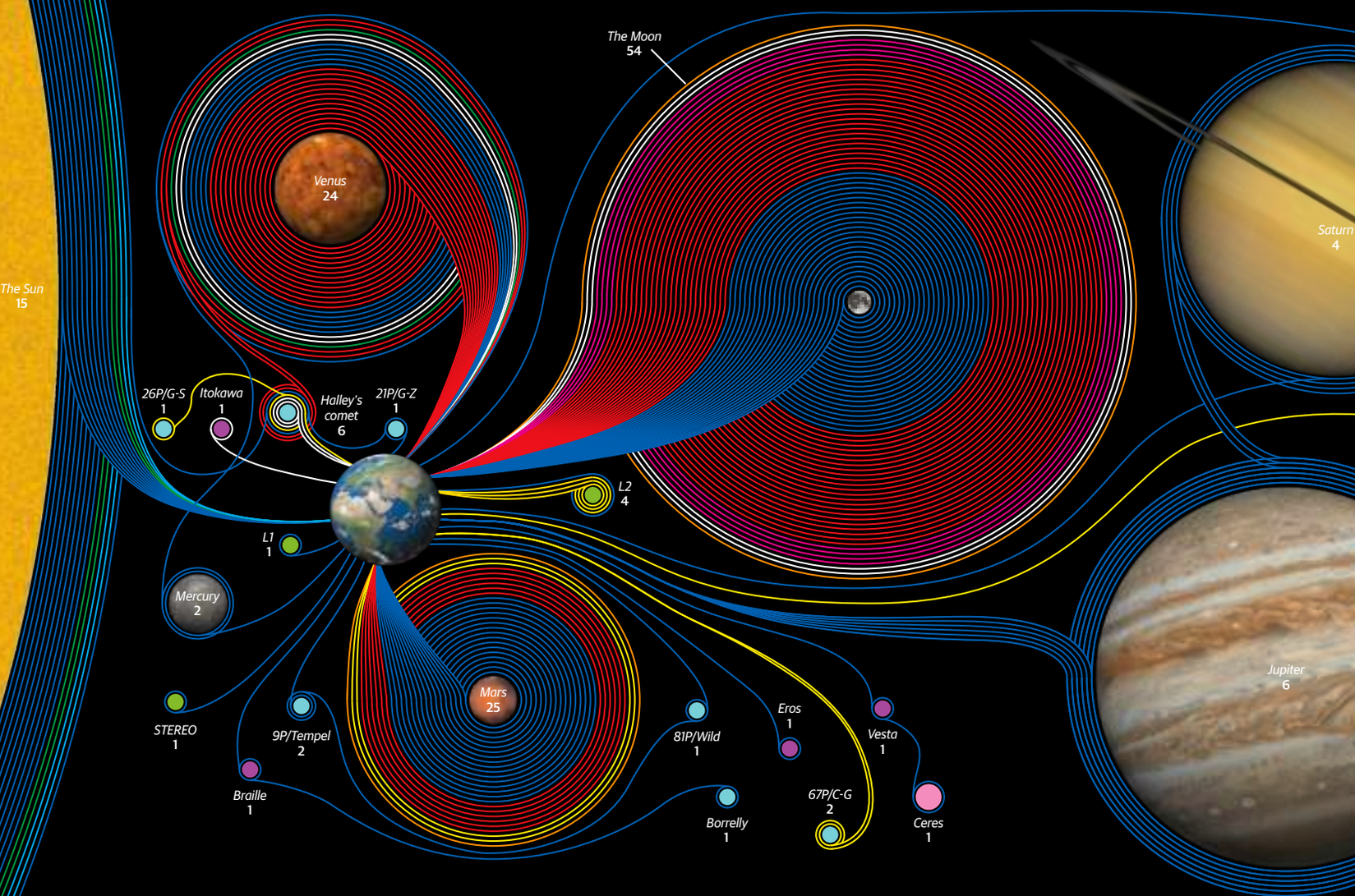


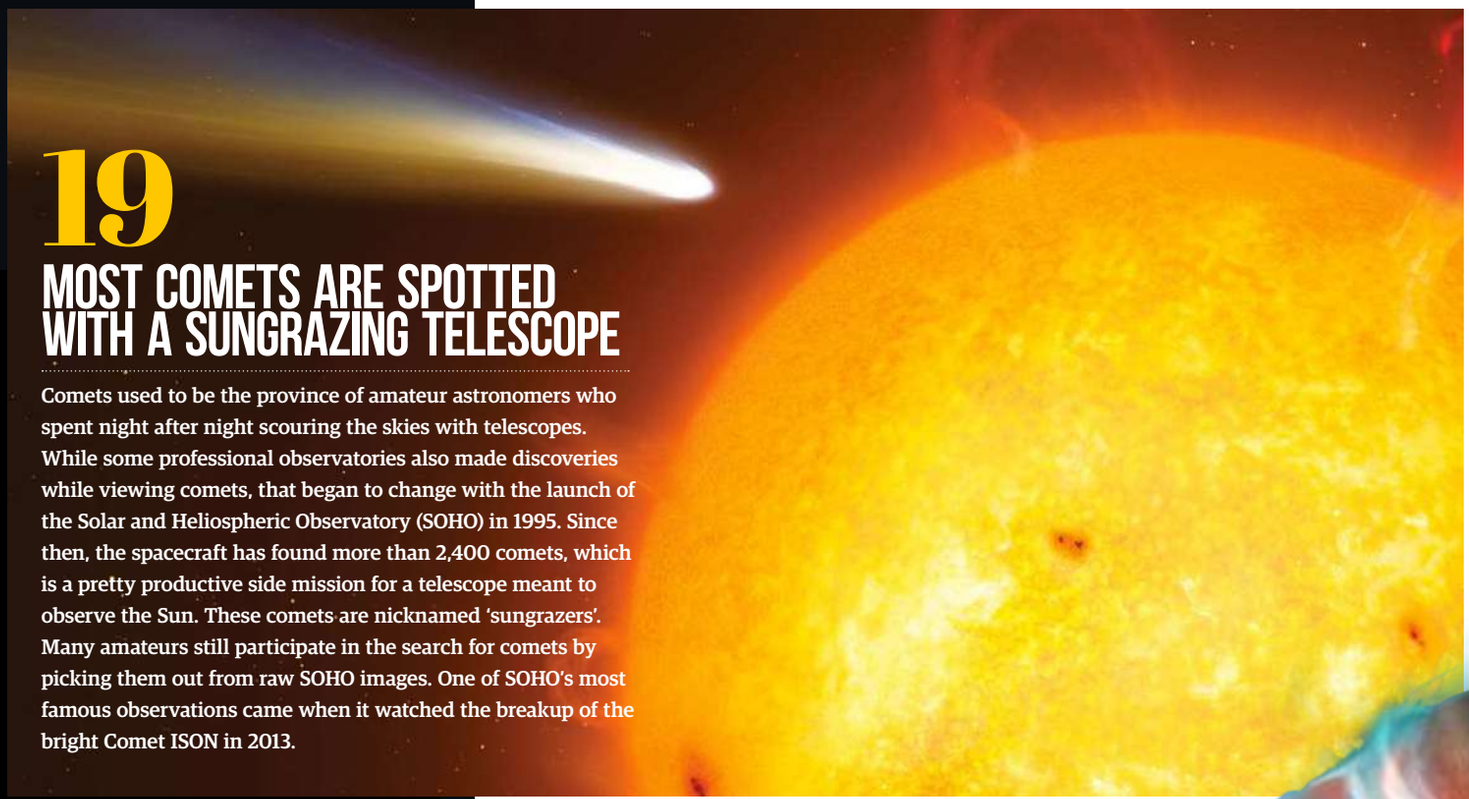
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18 WORLDS COULD BE CONTAMINATED BY SPACECRAFT

So far, scientists have found no evidence that life exists elsewhere in the Solar System. But as we learn more about how 'extreme' microbes live in underwater volcanic vents or frozen environments, more possibilities open up for where they could live on other planets.

Microbial life is now considered likely enough on Mars that scientists take special precautions to sterilise spacecraft headed to the planet. NASA chose to crash its Galileo spacecraft into Jupiter rather than risk it contaminating the potentially habitable oceans of Europa.

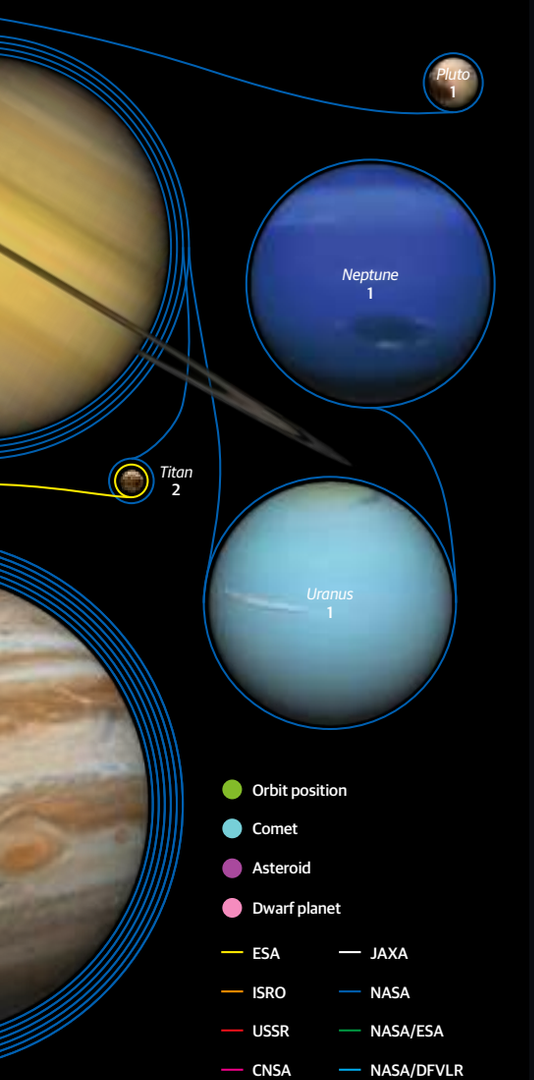


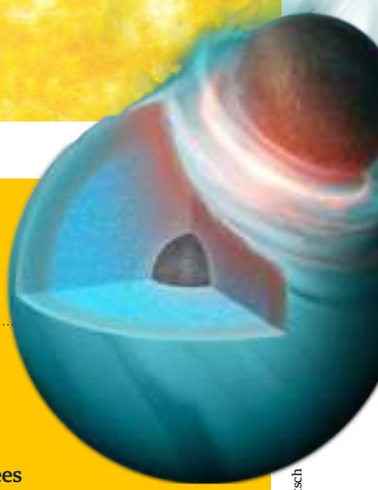


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19 MOST COMETS ARE SPOTTED WITH A SUNGRAZING TELESCOPE

Comets used to be the province of amateur astronomers who spent night after night scouring the skies with telescopes. While some professional observatories also made discoveries while viewing comets, that began to change with the launch of the Solar and Heliospheric Observatory (SOHO) in 1995. Since then, the spacecraft has found more than 2,400 comets, which is a pretty productive side mission for a telescope meant to observe the Sun. These comets are nicknamed 'sungrazers'. Many amateurs still participate in the search for comets by picking them out from raw SOHO images. One of SOHO's most famous observations came when it watched the breakup of the bright Comet ISON in 2013.





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20 URANUS SPINS SIDEWAYS

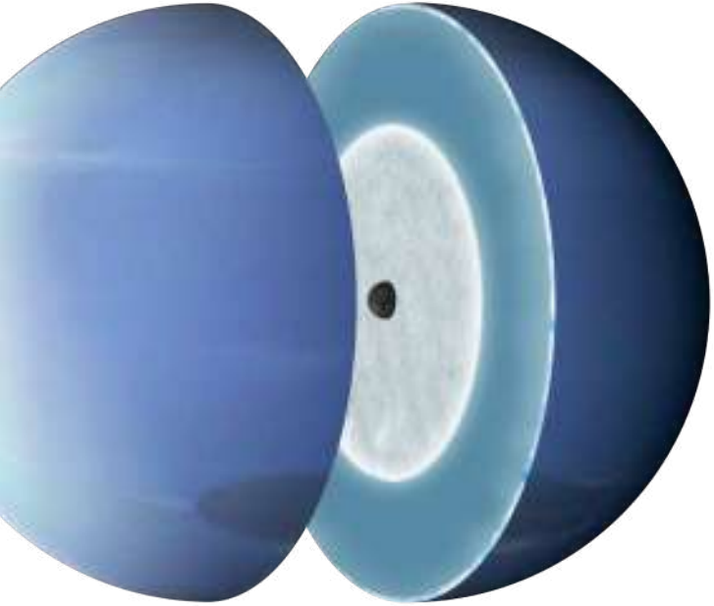
This gas giant of the outer Solar System is pretty weird on closer inspection. First, the planet rotates on its side, appearing to roll around the Sun like a ball. The most likely explanation for the planet's unusual orientation – about 90 degrees sideways compared to the other planets – is that it underwent some sort of titanic collision in the ancient past. Uranus' tilt causes what NASA considers to be the most extreme seasons in the Solar System. For about a quarter of each Uranus year – or 21 Earth years, as each Uranus year is 84 years long – the Sun shines directly over the north or south pole of the planet. That means for more than two decades on Earth, half of Uranus never sees the Sun at all.



© NASA/JPL-Caltech

21 WHAT HAPPENED TO MIRANDA?

One of the most bizarre moons in the outer Solar System is Miranda, a shadowy moon of Uranus observed only once when Voyager 2 got a glimpse in 1986. Miranda hosts sharp ridges, craters and other major disruptions on its surface that would usually be the result of volcanic action. Tectonic activity could cause that kind of surface, but Miranda is much too small to generate that kind of heat on its own. Researchers think that gravitational pull from Uranus could have generated the push-pull action needed to heat, churn and contort Miranda's surface. To know for sure, we'll need to send another spacecraft to check out the moon's unobserved northern hemisphere.



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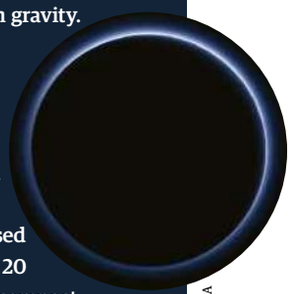
22 NEPTUNE IS TOO HOT

Neptune is roughly 30 times as far from the Sun as Earth, and it gets correspondingly less heat and light. But it radiates far more heat than it's taking in and has far more activity in its atmosphere than planetary scientists would suspect, especially compared to nearby Uranus. Uranus is closer to the Sun and yet radiates about the same amount of heat as Neptune, and scientists aren't sure why. Winds on Neptune can blow up to 2,400 kilometres (1,500 miles) per hour. Is all that energy coming from the Sun, from the planet's core or from gravitational contraction? Researchers are working to find out.

23 THERE ARE MOUNTAINS ON PLUTO

A tiny world at the edge of the Solar System, scientists assumed the dwarf planet would have a fairly uniform, crater-pocked environment. That changed when New Horizons flew by in 2015, sending back pictures that altered our view of Pluto forever. Among the astounding discoveries were icy mountains that are 3,300 metres (11,000 feet) high, indicating that Pluto must have been geologically active as little as 100 million years ago. Geological activity requires energy, and the source of that energy inside Pluto is a mystery. The Sun is too far away from Pluto to generate enough heat for geological activity and there are no large planets nearby that could have caused such disruption with gravity.

24 PLUTO ALSO HAS A BIZARRE ATMOSPHERE



Pluto's observed atmosphere broke all the predictions. As data from NASA's New Horizons flowed in, scientists analysed the haze and discovered some surprises. They found about 20 layers in Pluto's atmosphere that are both cooler and more compact than expected. This affects calculations for how quickly Pluto loses its nitrogen-rich atmosphere to space. The New Horizons team found that tonnes of nitrogen gas escapes the dwarf planet by the hour, but somehow Pluto can constantly resupply that lost nitrogen. The dwarf planet is likely creating more of it through geological activity.

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25 THERE MAY BE A HUGE PLANET AT THE SOLAR SYSTEM'S EDGE

In January 2015, California Institute of Technology astronomers Konstantin Batygin and Mike Brown announced - based on mathematical calculations and simulations - that there could be a giant planet lurking far beyond Neptune. Several teams are now on the search for the theoretical 'Planet Nine', and research suggests it could be located within the decade. This large object, if it exists, could help explain the movements of some objects in the Kuiper Belt, an icy collection of objects beyond Neptune's orbit. Brown has already discovered several large objects in that area that in some cases rivalled or exceeded the size of Pluto, but scientists are pursuing another theory, too - that Planet Nine could in fact be a grapefruit-sized black hole, warping space similarly to the way a gigantic planet would. Yet another team suggests that the weird movements of the far-flung Kuiper Belt occupants could be the collective influence of several small objects, not an undiscovered planet or black hole at all.

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Reported by Robert Lea

THOUGH IT WON'T HIT OUR PLANET FOR AT LEAST ANOTHER CENTURY, APOPHIS' SCIENTIFIC IMPACT IS TREMENDOUS

WILL AN ASTEROID HIT EARTH IN 2029?

© Getty

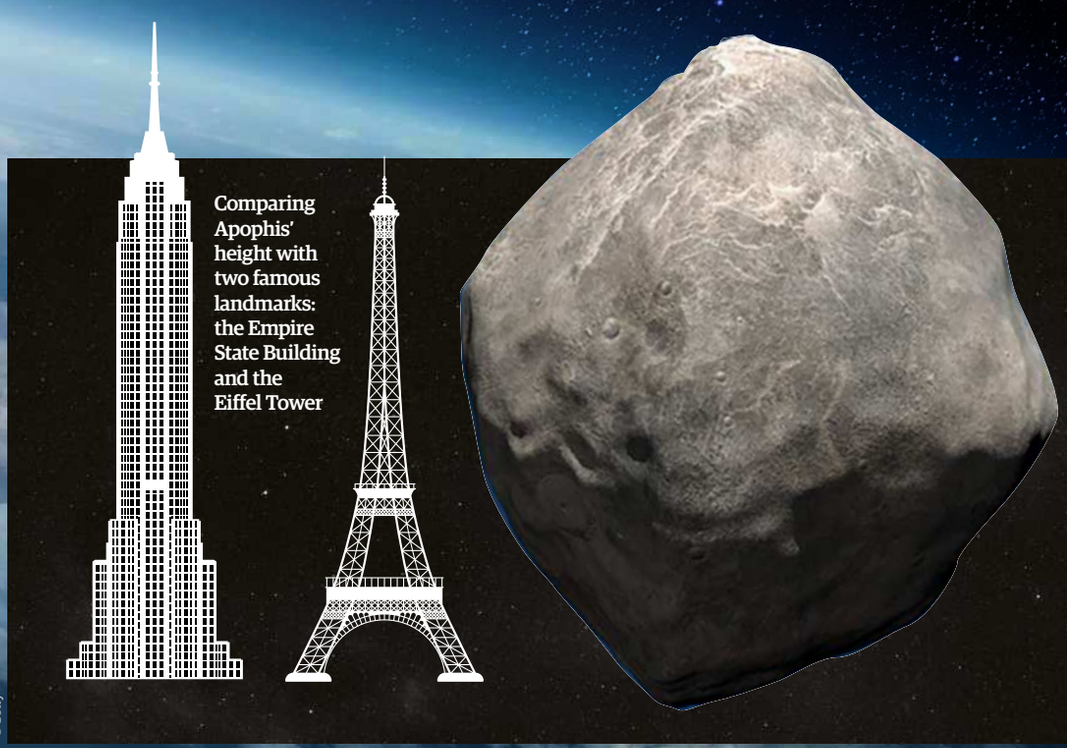
On Friday 13 April 2029, Earth will experience a dramatic close encounter with 99942 Apophis, with the 335-metre (1,100-foot) asteroid passing within 31,000 kilometres (19,000 miles) of our home planet, bringing it closer than most geostationary satellites. Thanks to Apophis' tremendous size, this close passage will be so bright that around 2 billion people will be able to witness it with the naked eye. First becoming visible in the Southern Hemisphere, the asteroid will resemble a speck of light as it streaks from east to west, initially passing over Australia, traversing the Indian Ocean and eventually crossing the equator over Africa.

This spectacular and historic event could have been much more severe. Scientists were unsure whether the passage of Apophis would result in a collision with Earth. Even when this risk was negated, researchers still couldn't rule out the possibility that Earth's gravitational effects could influence the asteroid in such a way that one of its next visits could result in an impact - something that was only ruled out this year.

"Apophis is in the category of potentially hazardous asteroids (PHAs) - asteroids with orbits that bring them very close to Earth now and for centuries in the future," says Richard Binzel, professor of planetary sciences at the Massachusetts Institute of Technology (MIT) and a leading scientist in the field of asteroid research. "What makes Apophis the poster

WHAT IS AN ASTEROID?

Asteroids are the shattered remains of planetesimals – objects that never grew large enough to become planets. There are millions of asteroids in the Solar System, distinguished from comets as they are formed from rock rather than dust and ice.



Comparing Apophis' height with two famous landmarks: the Empire State Building and the Eiffel Tower

©Getty

child for potentially hazardous asteroids is that it will make the closest known approach to Earth of any large asteroid this decade. But Apophis will miss the Earth."

Though we now know Apophis won't strike Earth in the near future, the fact that this asteroid has sat at the top of the European Space Agency's (ESA) 'impact risk list' of PHAs and NASA's Sentry Risk Table for 17 years – and its forthcoming visits – means its time as an object of intense scientific interest is just beginning.

Apophis was discovered on 19 June 2004 by Roy A. Tucker, David J. Tholen and Fabrizio Bernardi while they were working at the Kitt Peak National Observatory in Arizona, receiving the designation 2004 MN4. Though the team was only able to observe the asteroid for two days as a result of technical issues and unfavourable weather conditions, further observations quickly revealed a wealth of details about the asteroid.

In 2005 the asteroid was renamed 'Apophis' after the Greek name for an ancient Egyptian representation of evil and chaos, a serpent that dwells in darkness and frequently attempts to devour the Sun-god Ra as he makes his passage across the sky. In the same year that Apophis received its new moniker, Binzel was part of a team that used reconnaissance telescopic observations to measure the colour properties of Apophis and determine its composition, finding it resembles the most common class of meteorites, known as 'ordinary chondrites'.

Classified as an 'S-type', or siliceous asteroid, Apophis is composed mostly of silicates, with a mix of metals like nickel and iron. Its shape is believed to be elongated and comprises two lobes – almost like a rocky space peanut. "Apophis is a piece of an early Solar System planetesimal – a planetary building block – that never coalesced into one of our Solar System's planets.

"It has been stored in the asteroid belt for 4.6 billion years, and may be a fragment of a larger asteroid that broke apart in a collision in the asteroid belt," says Binzel. "That collision may have cast the fragment we call Apophis on a trajectory that resulted in its current orbit that comes very close to Earth."

The excitement of Apophis' discovery quickly turned to concern when researchers calculated just how close the asteroid's orbit would bring it to Earth. Using radar astrometry, researchers found a probability of around 2.7 per cent that the PHA would hit Earth in 2029. These estimates may seem low, but were still extreme enough to give Apophis the highest values on two systems used by astronomers to calculate how dangerous an asteroid is to our planet: the Torino scale, devised by Binzel, and the Palermo Technical Impact Hazard Scale.

By 2006 the probability of an impact in 2029 was all but negated, yet the threat presented by Apophis couldn't be as easily discounted. "Apophis will be so close in 2029 that Earth's gravity will significantly change its orbit. The trajectory of Apophis after 2029 depends on its exact position at the time of the encounter,"

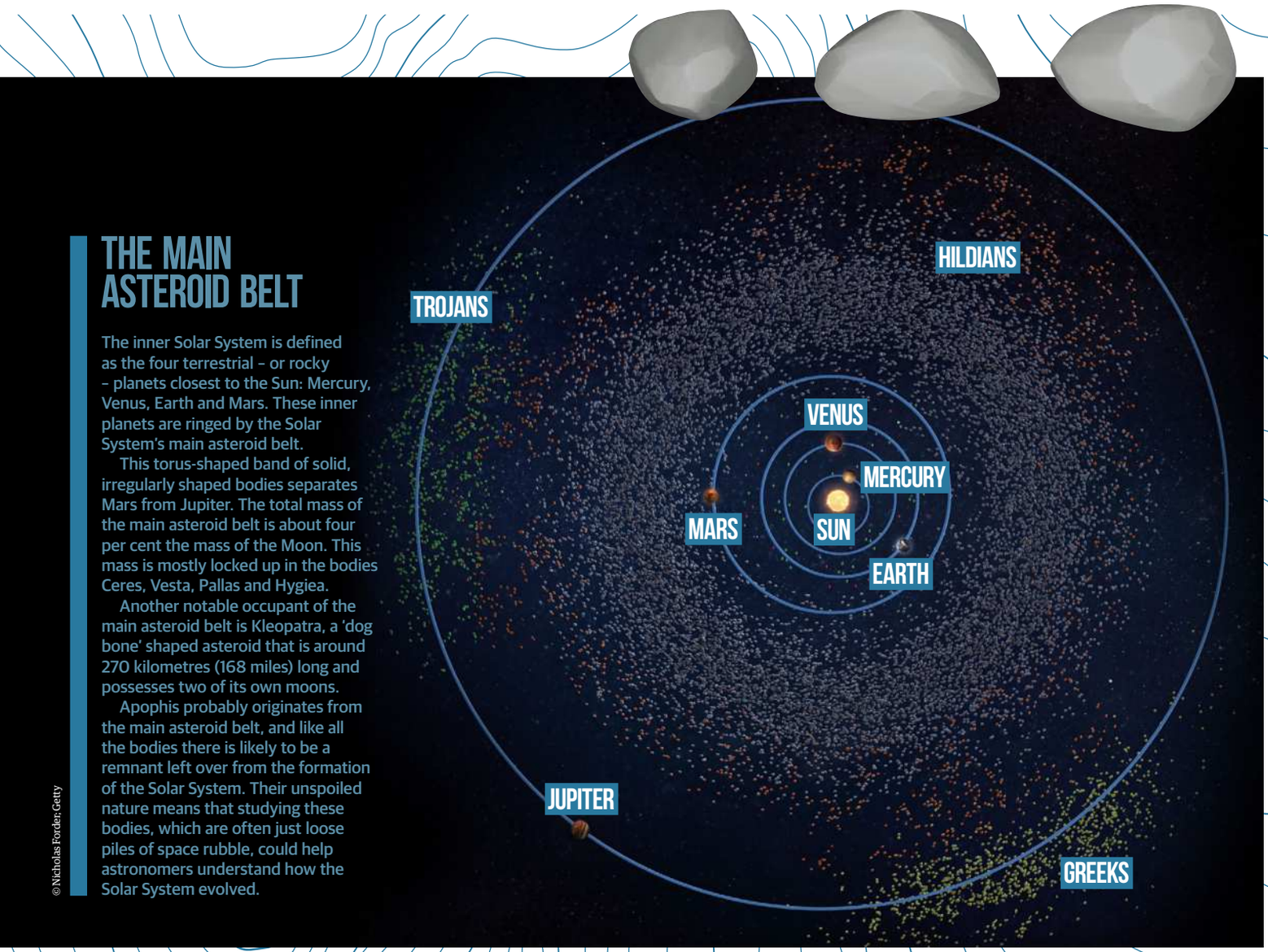
THE MAIN ASTEROID BELT

The inner Solar System is defined as the four terrestrial – or rocky – planets closest to the Sun: Mercury, Venus, Earth and Mars. These inner planets are ringed by the Solar System's main asteroid belt.

This torus-shaped band of solid, irregularly shaped bodies separates Mars from Jupiter. The total mass of the main asteroid belt is about four per cent the mass of the Moon. This mass is mostly locked up in the bodies Ceres, Vesta, Pallas and Hygiea.

Another notable occupant of the main asteroid belt is Kleopatra, a 'dog bone' shaped asteroid that is around 270 kilometres (168 miles) long and possesses two of its own moons.

Apophis probably originates from the main asteroid belt, and like all the bodies there is likely to be a remnant left over from the formation of the Solar System. Their unspoiled nature means that studying these bodies, which are often just loose piles of space rubble, could help astronomers understand how the Solar System evolved.



Source: Wikipedia Commons © Astronomical Institute of the Charles University

© Nicholas Forder; Getty

says Davide Farnocchia, who joined NASA's Jet Propulsion Laboratory (JPL) in 2012, helping to conduct the analysis of the asteroid's trajectory. "If Apophis passed through specific gravitational keyholes, the gravity of Earth would tweak its orbit by just the right amount – or should I say the wrong amount – to put it on a collision course in a later year."

Even after a 2036 impact had been mostly ruled out – Apophis won't actually come that close to Earth during this passage – a gap in observations of the asteroid from 2015 to 2019, caused by its position close to the Sun, prevented an impact in 2068 or later from being dismissed. The asteroid seemed almost stubbornly determined to live up to its apocalyptic name. At least until this year, when Farnocchia and his team resolved to tackle the problem head-on.

"At JPL's Center of Near-Earth Object Studies (CNEOS), we compute high-precision trajectories and assess the possibility of future impacts for all known asteroids," says Farnocchia. "That's our daily bread and butter." But unseating Apophis from the top of various space agencies' 'risk lists' was no easy feat, and required a much better determination of the asteroid's orbit. To obtain this, Farnocchia and the CNEOS team took the results from a radar observation campaign and optical studies carried out in late 2020 and early 2021. They then combined these observations with previously collected data.

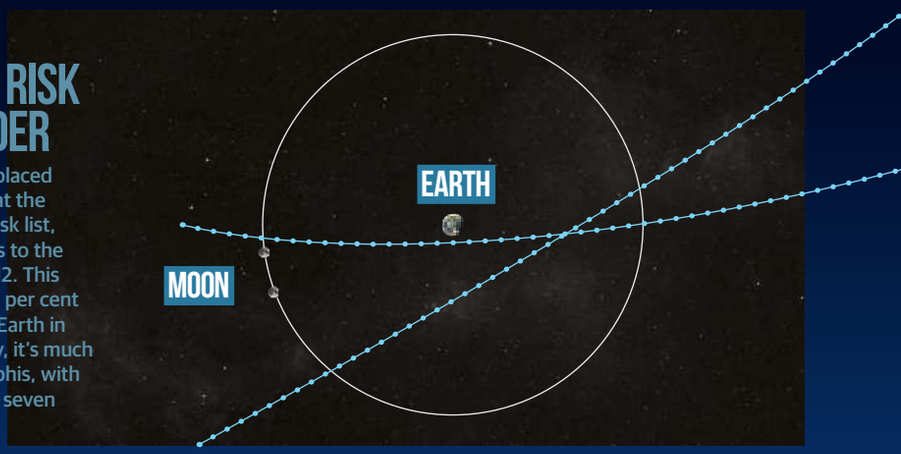
"Apophis has been extensively tracked since its discovery by both optical and radar telescopes," says Farnocchia. "Thanks to the data collected by astronomers all over the world, we can precisely predict the motion of Apophis through the April 2029 flyby." The team was able to calculate that the orbital period of Apophis will be stretched from 0.9 to 1.2 years as a result of its 2029 encounter with Earth.

Significantly, the CNEOS crew was also able to model how close Apophis will come to the gravitational keyholes that correspond to causing impacts in both 2036 and 2068. "The information provided by the 2020 and 2021 observations shrank uncertainties enough to ensure that Apophis will miss all the major gravitational keyholes in 2029," says Farnocchia, "allowing us to rule out any impact for the next 100 years." Breathing easier with the knowledge that Apophis won't strike our planet within the next century, we can speculate a little about the consequences of such a collision.

Considering what an impact between our planet and an asteroid the size, shape and

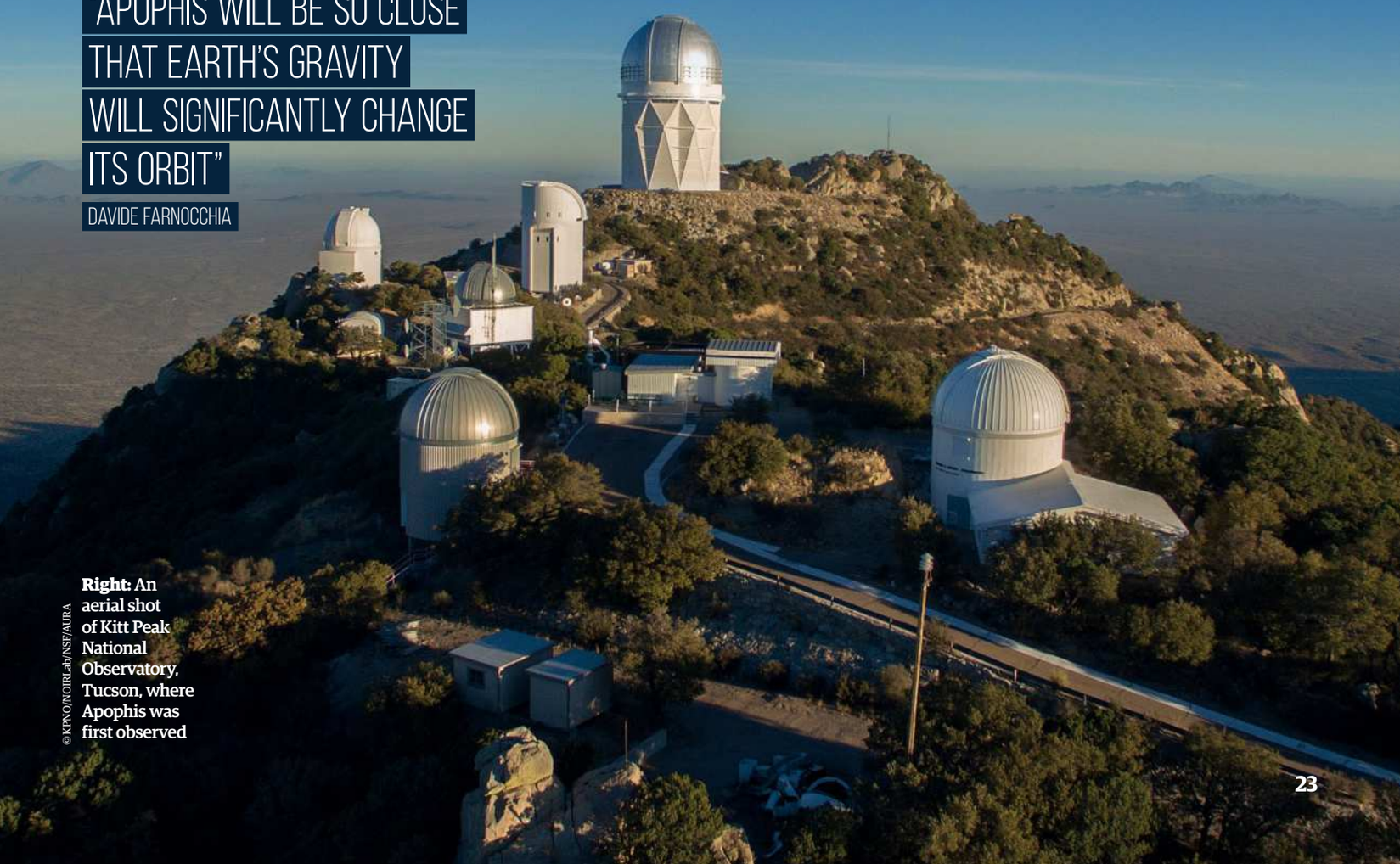
THE NEW RISK LIST LEADER

With Apophis displaced from its position at the top of the ESA's risk list, pole position goes to the asteroid 2010 RF12. This asteroid has a 4.6 per cent chance of hitting Earth in 2095. Fortunately, it's much smaller than Apophis, with a diameter of just seven metres (22 feet).



"APOPHIS WILL BE SO CLOSE THAT EARTH'S GRAVITY WILL SIGNIFICANTLY CHANGE ITS ORBIT"

DAVIDE FARNOCCHIA



Right: An aerial shot of Kitt Peak National Observatory, Tucson, where Apophis was first observed

© KPNO/NOIRLab/NSF/AURA

density of Apophis would look like is not an easy task. There certainly isn't anything like it in the geological record of our planet, and there are many factors that have to be considered when estimating the damage that could arise from such a collision. These factors include asteroid size, density and mass, as well as the angle and velocity at which the asteroid strikes.

Professor Gareth Collins from the Department of Earth Science and Engineering at Imperial College London studies impacts within the Solar System and is one of the developers of Earth Impact Effects, a program that allows users to input data from asteroids and create some estimates about an impact between our planet and that particular body. "We have run simulations of an impact between Apophis and Earth, but the outcome of an Apophis-scale impact with Earth is very uncertain," Collins says. "Size and speed are the main factors, but the nature of the target site is also important – if the impact occurs in the ocean it can generate hazardous tsunamis; on land, a lot more ejected dust is produced. And, of course, a major factor is how close the impact happens to human populations."

Collins estimates that if Apophis were to strike Earth at 20 kilometres (12.4 miles) per second – the average speed of asteroid impacts – the energy released would be about 10^{18} joules. "This is equivalent to the explosive yield of the global nuclear arsenal," he adds. "About 100,000 times more than the energy of the Chelyabinsk meteor and a million times more energy than the bombs dropped on Hiroshima."

The researcher goes on to explain that the worst-case scenario for an impact would be if it were to occur close to a large population centre or near a heavily populated coastline. If this occurred, devastating consequences would arise from a number of secondary effects, such as violent ground shaking to intense thermal radiation and atmospheric shock waves.

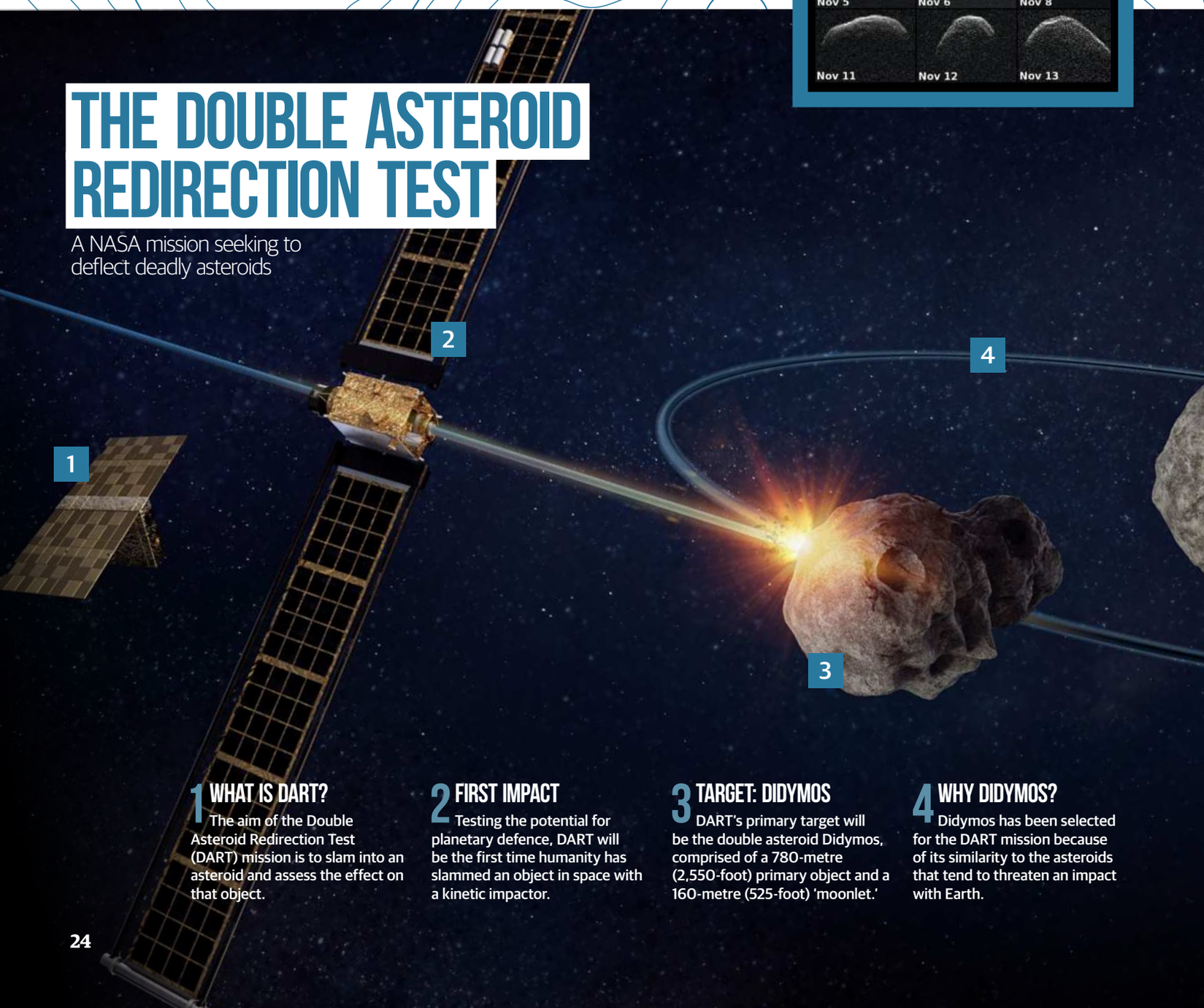
"Unless an asteroid similar to Apophis hits Earth and we can measure the consequences, our program will remain a 'best guess' and subject to large uncertainties," Collins adds. "But close



©NASA/JPL-Caltech

THE DOUBLE ASTEROID REDIRECTION TEST

A NASA mission seeking to deflect deadly asteroids



1 WHAT IS DART?

The aim of the Double Asteroid Redirection Test (DART) mission is to slam into an asteroid and assess the effect on that object.

2 FIRST IMPACT

Testing the potential for planetary defence, DART will be the first time humanity has slammed an object in space with a kinetic impactor.

3 TARGET: DIDYMOS

DART's primary target will be the double asteroid Didymos, comprised of a 780-metre (2,550-foot) primary object and a 160-metre (525-foot) 'moonlet.'

4 WHY DIDYMOS?

Didymos has been selected for the DART mission because of its similarity to the asteroids that tend to threaten an impact with Earth.



COMPARING APOPHIS TO THE 'DINOSAUR KILLER'

The most infamous asteroid strike is that of the Chicxulub Impactor 66 million years ago. This 10 to 15 kilometre (6.2 to 9.3 mile) asteroid struck the Yucatán Peninsula in Mexico, generating an estimated energy equivalent to 21 to 921 billion Hiroshima bombs, wiping out the dinosaurs.

Below: The Legacy Survey of Space and Time (LSST) conducted at the Vera C. Rubin Observatory will survey near-Earth objects

© NASA

Because Apophis seems to be similar to around 80 per cent of the PHAs thus far identified by scientists, this means collecting data about these qualities grants researchers a unique opportunity to learn about a broad range of objects – and how we might divert them should they threaten Earth like Apophis once did. "Knowing how PHAs are put together might be some of the most valuable knowledge ever obtained in the event we ever have to put that knowledge to use to defend our planet from some future asteroid impact," Binzel adds. The true legacy of Apophis may be the insight it grants us, which might help successfully divert a PHA, meaning though this asteroid may never itself impact the Earth's surface, its scientific impact could be immeasurable.

Beyond this, however, the passage of Apophis in 2029 is a historic spectacle that shouldn't be missed. "Objects the size of Apophis come this close to Earth approximately once every thousand years on average," concludes Farnocchia. "Apophis is going to be so close in 2029 that it will be visible to the naked eye. It's going to be as bright as the stars in Ursa Minor. Don't miss the chance to see it... I know I won't!"



Robert Lea
Space science writer
Rob is a science writer with a degree in physics and astronomy. He specialises in physics, astronomy, astrophysics and quantum physics.

"SIZE AND SPEED ARE THE MAIN FACTORS, BUT THE NATURE OF THE TARGET SITE IS ALSO IMPORTANT"

GARETH COLLINS

approaches do help us better understand asteroids and their likelihood of striking Earth in future."

With the threat of an impact from Apophis negated for a while, researchers can now focus on the collection of scientific information from its flybys. With eight years of planning still remaining before the visit, the sky really is the limit for the Apophis investigation. "The 2029 flyby is a reminder that asteroids of considerable size can come close to and potentially reach Earth," says Farnocchia. "But the fact that we have known about this flyby since 2004 shows that our asteroid search-and-track programs and orbital calculations can allow us to discover and predict these events well in advance."

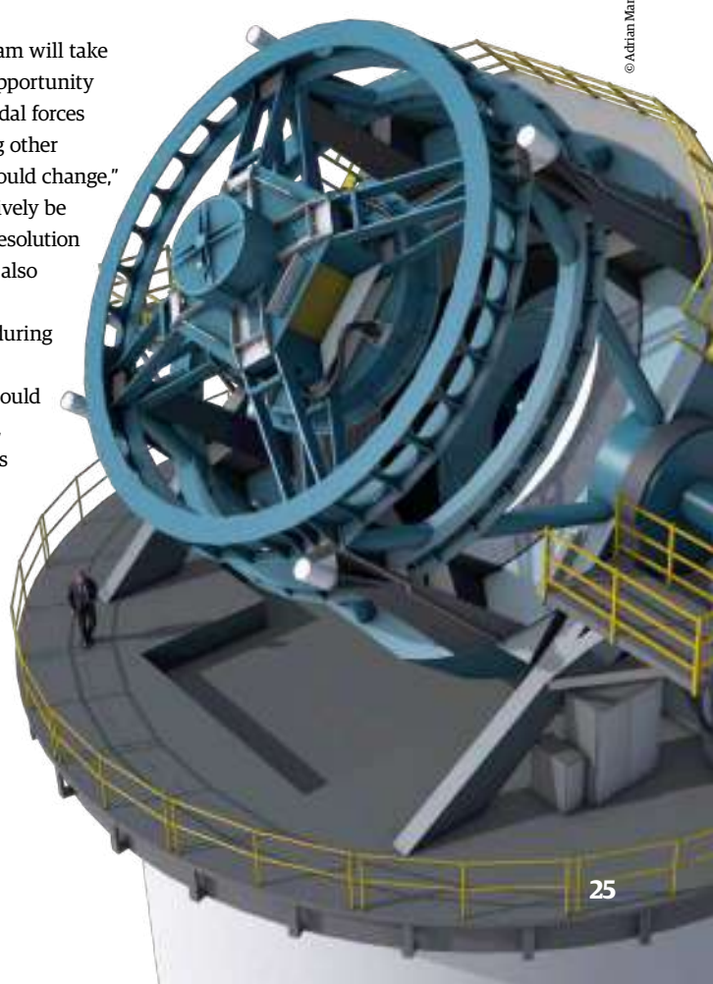
In particular, Farnocchia and his team will take advantage of this valuable scientific opportunity by observing how Apophis reacts to tidal forces when it gets so close to Earth. "Among other things, the rotation state of Apophis could change," says Farnocchia. "Apophis will extensively be observed from the ground, and high-resolution radar data will be collected. There are also spacecraft missions to Apophis under consideration to analyse the asteroid during and after the close encounter."

Observations of Apophis in 2029 should help scientists better ascertain its size, shape, composition and even model its interior. "By watching how Apophis might shake, rattle and roll, even just by a tiny amount, we will learn how it is put together on its inside," says Binzel, comparing this to how seismic waves travelling through Earth, the Moon and Mars have been used to model beneath their surfaces. "Interior structure for a potentially hazardous asteroid is something we have never measured before. Apophis might just give us that chance."



5 DART MISSION LAUNCH
DART is all set to launch aboard a SpaceX Falcon 9 rocket in November 2021. It will intercept Didymos in September 2022.

© Nicholas Forder



© Adrian Mann



NASA's DART mission conducted an asteroid redirection test

© NASA

USER MANUAL

DART MISSION

THE SPECS

Launch: 24 November 2021

Launch rocket: SpaceX Falcon 9

Target: Didymos and Dimorphos

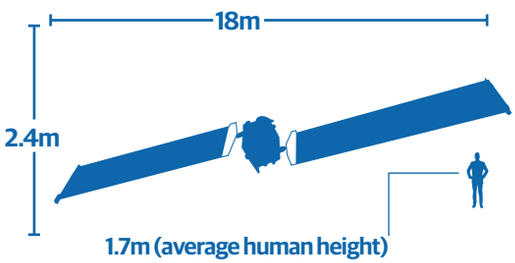
Operators: NASA

Orbital inclination: Halo orbit

Estimated cost:
$313.9 million (£227.9 million)

DART impact:
26 September 2022

Distance from Earth: 11 million kilometres (6.8 million miles)



NASA's Double Asteroid Redirection Test (DART) was an ambitious project designed to test a method of deflecting an asteroid for the purpose of planetary defence using the kinetic impactor technique. DART was launched on 24 November 2021, and the spacecraft reached its destination at its scheduled arrival time at its target in late September 2022. DART's target was a binary near-Earth asteroid: Didymos and its moonlet Dimorphos. DART is the first planetary defence mission to test asteroid deflection methods.

DART deliberately impacted the moonlet Dimorphos at speeds of 6.6 kilometres (4.1 miles) per second. The impact was hypothesised to cause the moonlet's orbital speed to change by a fraction of a percent, a slight shift that should be enough to change its orbital period by several minutes. The initial impact proved successful, but the change in Dimorphos' orbit around Didymos will be observed and measured by telescopes on Earth in order to conclusively prove whether the mission has been a success. Though the threat from asteroid impacts is small, it's a threat to life on Earth nonetheless, and something we should be prepared for. We only need to look at past impact events, such as the massive Chicxulub asteroid impact that is credited with the extinction of the dinosaurs 65 million years ago, to see the catastrophic effects an impact can have on life on Earth.

Early detection of near-Earth asteroids is the first step in planetary defence. Approximately 30 new discoveries of near-Earth asteroids are made each week, and at the start of 2019 there were more than 19,000 known near-Earth asteroids. DART will be the first mission to test an asteroid deflection technique.

The DART mission was a joint endeavour by NASA and Johns Hopkins University's Applied Physics Laboratory (APL). The mission's target is the binary asteroid system Didymos, which means 'twin' in Greek. The system consists of a near-Earth asteroid, 65803 Didymos, measuring 780 metres (2,560 feet) across and its moonlet Dimorphos, which measures 160 metres (525 feet) across.

Though the pair are not a threat to Earth, they were perfect candidates for the DART mission since Dimorphos is around the same size as an asteroid that could pose the most likely threat to Earth if it were on a collision course with the planet. Their orbit around the Sun is also close enough to Earth for ground-based telescopes to observe and measure any differences after the collision.



"DART IS THE FIRST PLANETARY DEFENCE MISSION TO TEST ASTEROID DEFLECTION METHODS"

ANATOMY OF DART

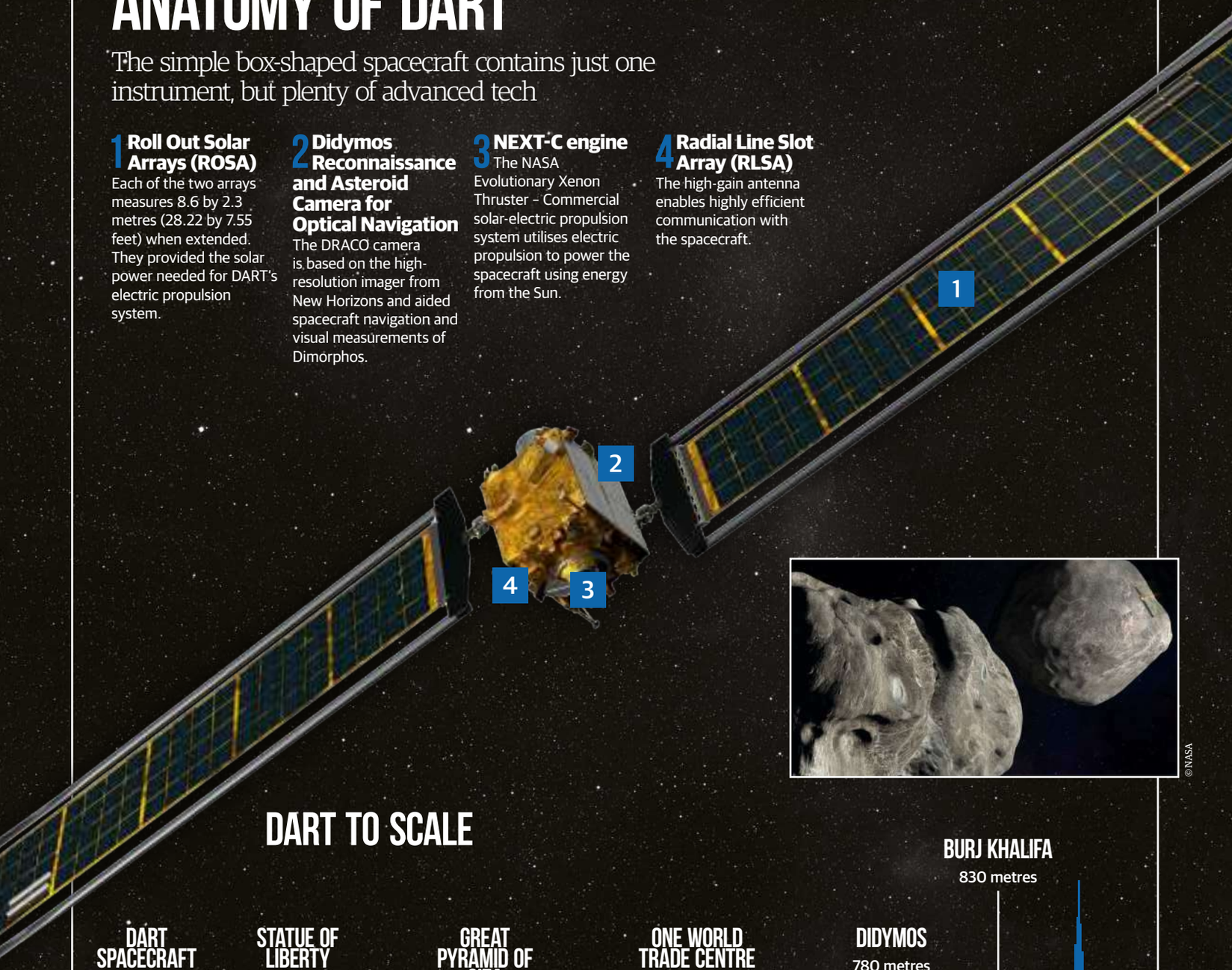
The simple box-shaped spacecraft contains just one instrument, but plenty of advanced tech

1 Roll Out Solar Arrays (ROSA)
Each of the two arrays measures 8.6 by 2.3 metres (28.22 by 7.55 feet) when extended. They provided the solar power needed for DART's electric propulsion system.

2 Didymos Reconnaissance and Asteroid Camera for Optical Navigation
The DRACO camera is based on the high-resolution imager from New Horizons and aided spacecraft navigation and visual measurements of Dimorphos.

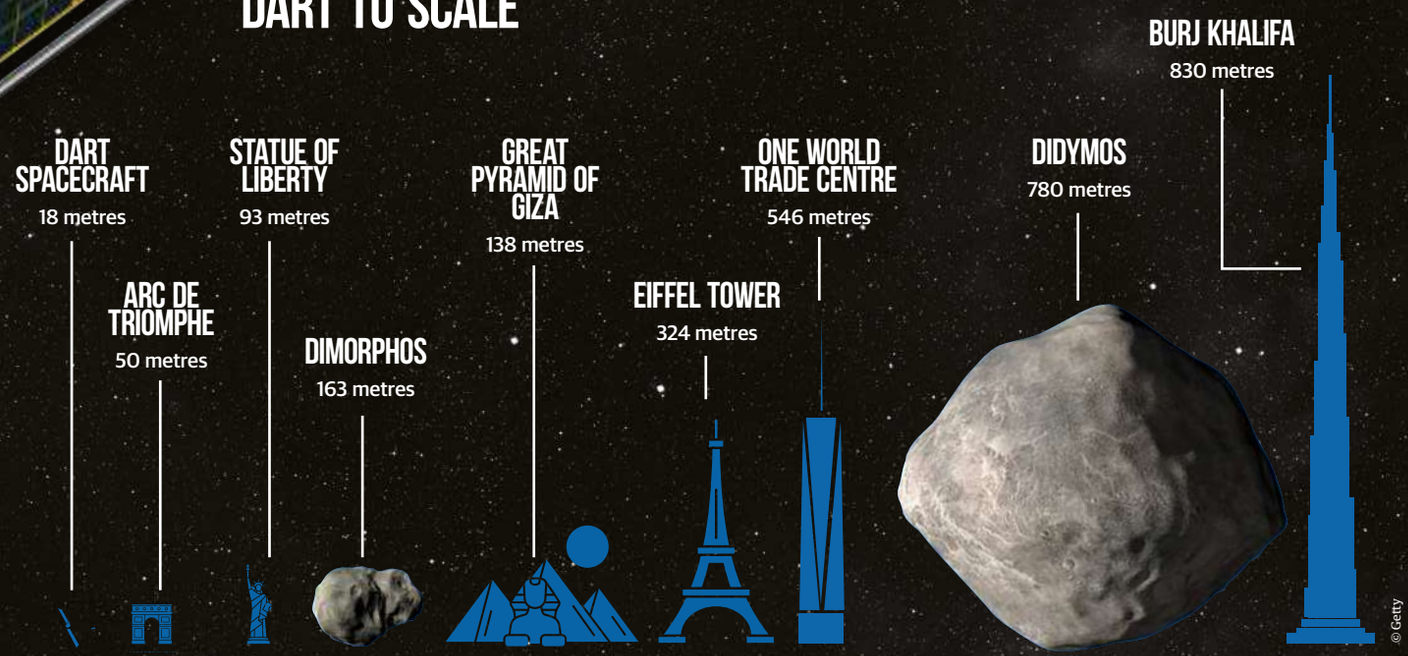
3 NEXT-C engine
The NASA Evolutionary Xenon Thruster – Commercial solar-electric propulsion system utilises electric propulsion to power the spacecraft using energy from the Sun.

4 Radial Line Slot Array (RLSA)
The high-gain antenna enables highly efficient communication with the spacecraft.



© NASA

DART TO SCALE



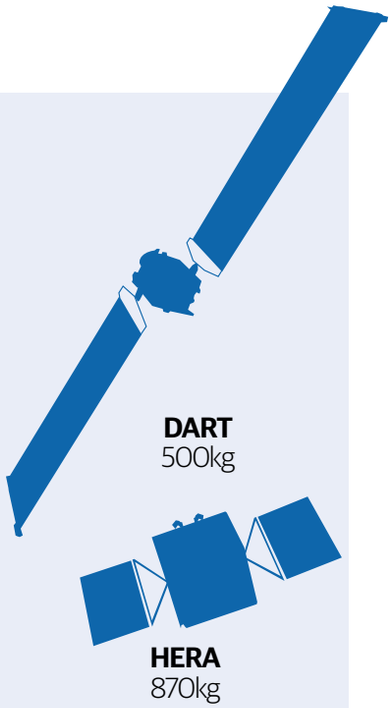
© Getty

HEAD TO HEAD

DART VS HERA

The European Space Agency's (ESA) Hera will conduct post-impact investigations of DART's collision. The spacecraft is planned to launch in 2024 and reach the Didymos system in 2026. The ESA's Hera spacecraft will be joined by two cubesats. Together they will carry out surveys of both Didymos and Dimorphos, paying particular attention to the crater left by DART's impact. The Hera mission also aims to determine a precise mass of Dimorphos.

Though the two missions are designed and operated independently, together they will advance our understanding of planetary defence technologies. Members from both missions are part of an international collaboration known as Asteroid Impact and Deflection Assessment (AIDA), a large international collaboration between the ESA, German Aerospace Center, the Observatoire de la Côte d'Azur, NASA and APL.



DART
500kg

HERA
870kg

DART was a simple spacecraft. The box-shaped main vehicle measured roughly 1.2 by 1.3 by 1.3 metres (3.9 by 4.3 by 4.3 feet) - about the size of a refrigerator. Each of the two large solar arrays is 8.5 metres (27.9 feet) long when fully deployed. The DART spacecraft contained just one instrument, the Didymos Reconnaissance and Asteroid Camera for Optical Navigation (DRACO). It turns out that if your primary goal is to smash into an asteroid, you don't need to take a lot with you.

Once DART launched on its SpaceX Falcon 9, it deployed its Roll Out Solar Arrays (ROSA) to power itself for the journey to Didymos. Scientists tested the ROSA arrays on board the International Space Station in June 2017, and they were deemed suitable to provide the power required to support DART's electric propulsion system. In fact, NASA is adding larger versions of the ROSA arrays to the space station's own power grid. The DART spacecraft used the next-generation, fuel-efficient

HOW TO DEFEND EARTH AGAINST AN ASTEROID

1 Find the asteroid
Ground and space-based telescopes are used to identify near-Earth objects (NEOs) that could pose a threat when entering Earth's neighbourhood.

2 Track the asteroid
When an NEO is detected, scientists map its orbit and make repeated observations to assess whether it's on a collision course with Earth.

3 Characterise the asteroid
Scientists then characterise the asteroid to determine orbit trajectory, size, shape, mass and composition to better understand how to deflect it.

4 Deflect the asteroid
There are three main techniques to deflect an asteroid: use gravity to pull the asteroid off course, smash a spacecraft into the asteroid or use lasers to vaporise the asteroid.

5 Global coordination
An impact would affect the world, and needs a cohesive worldwide response effort. Planetary defence requires advanced coordination and education of NEO threats.

NASA Evolutionary Xenon Thruster – Commercial (NEXT-C) solar-electric propulsion system as part of its in-space propulsion.

DART was guided to its target Dimorphos by sophisticated autonomous navigation software. It's no easy feat to locate a target that's 160 metres (525 feet) in diameter and 11 million kilometres (6.8 million miles) from Earth. The navigation software was designed to identify both Didymos and Dimorphos and distinguish between the two so that DART could be directed to the smaller body, Dimorphos, for its impactful mission.

As the spacecraft approached its target, DRACO, the onboard high-resolution camera, helped navigate the DART spacecraft and take measurements of the target asteroid, including the size and shape of Dimorphos.

But the DART spacecraft wasn't making its journey to the near-Earth asteroid binary alone. The spacecraft was joined by LICIACube, or the Light Italian Cubesat for Imaging Asteroids. LICIACube is a CubeSat contributed by the Italian Space Agency and built by Italian aerospace engineering company Argotec. The LICIACube weighs just 14 kilograms and measures roughly the length of an adult's hand and forearm. The little CubeSat has a very important job, and was deployed by DART on 11 September 2022, 15 days before the spacecraft impacted Dimorphos. LICIACube hung back and witnessed the impact, capturing images of the collision to help researchers verify the efficacy of the impact – and that we got to see on our TV screens.

"DART WAS GUIDED TO ITS TARGET DIMORPHOS BY SOPHISTICATED AUTONOMOUS NAVIGATION SOFTWARE"

DART BY NUMBERS

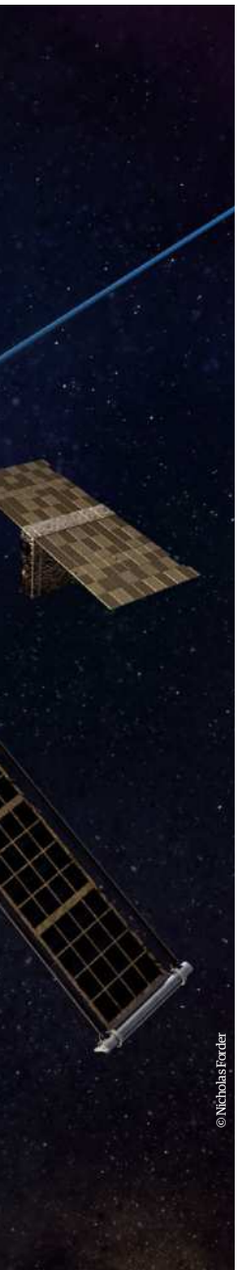
19,000
Number of near-Earth asteroid discoveries

8.6M
Length of each of DART's ROSA arrays

1.18KM
Distance between Didymos and Dimorphos

11.92
Orbital period of Dimorphos in hours

23 JUNE 2020
The asteroid moonlet Dimorphos was formally named by the International Astronomical Association


© Nicholas Forder

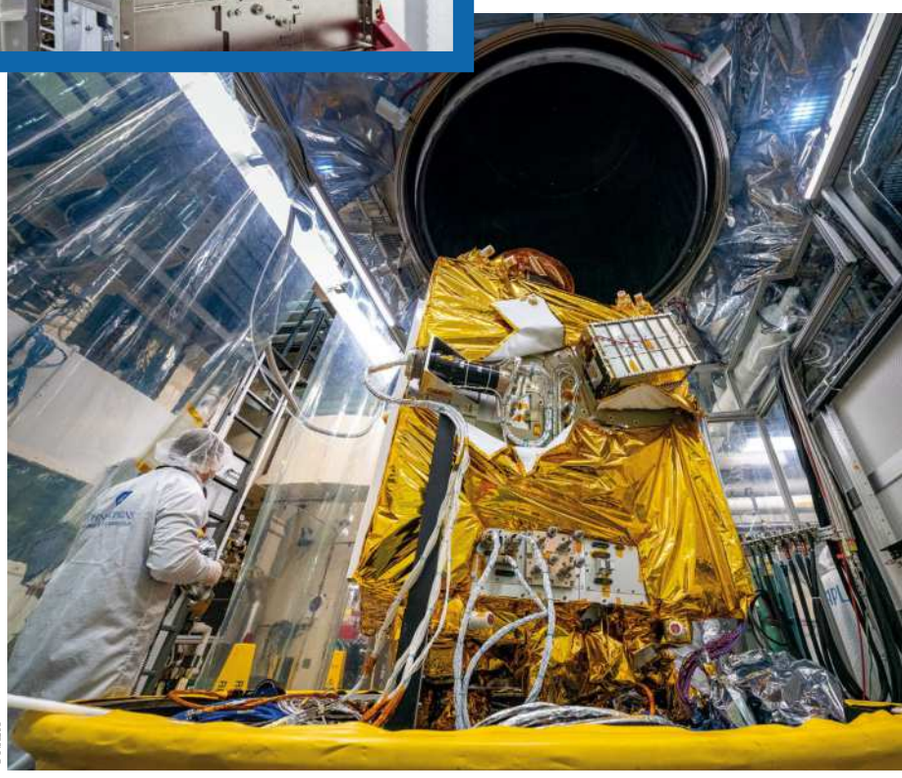
TOP TECH

ROLL OUT SOLAR ARRAYS (ROSA)

The DART spacecraft's arrays were crucial for enabling the spacecraft to reach its target Dimorphos. The impressive solar arrays are light and compact, and slowly unfurled to reach 8.5 metres (27.9 feet) in length – about the length of a bus. The arrays were first tested on the International Space Station in 2017, and DART was the first spacecraft to fly the new arrays, paving the way for future missions.




© NASA


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Above: LICIACube witnessed DART's impact with Dimorphos. In this image, a team of engineers inspects the LICIACube at the Johns Hopkins Applied Physics Laboratory

Right: DART had a backup launch plan but ended up launching on time, with the mission going to plan

GOING BACK TO THE MOON

SOON, NASA WILL TAKE THE FIRST STEP IN RETURNING ASTRONAUTS TO THE LUNAR SURFACE

Reported by Colin Stuart

It's been a long time since a human voice bellowed from the lunar surface. This year marks half a century since Apollo astronaut Gene Cernan left the last footprints on the Moon in 1972, and a lot has changed since then. That year the first scientific handheld calculator was released; today we carry more computing power in our pocket than that which safely guided the Apollo astronauts to the Moon and back.

Now, at long last, humanity is about to leave low-Earth orbit (LEO) once again. Only two dozen astronauts have achieved that feat so far, all of them white men. Soon the first female astronaut and astronaut of colour will join the lauded lists of moonwalkers. It's all thanks to the Artemis program – NASA's plan to explore more of the lunar surface than ever before. By 2025 we could see astronauts walk in the lunar dust once more, with the upgrade from grainy black-and-white video footage that half a century of technological progress will bring. A whole new generation could see themselves as budding space travellers, inspired to dream big.



THE SPACE LAUNCH SYSTEM

It takes a lot of power to send 26 tonnes worth of cargo to the Moon

1 FOUR RS-25 ENGINES

NASA claims they're the most efficient engines ever built.

2 SOLID ROCKET BOOSTERS

Each one is the height of a 17-storey building.

3 CORE STAGE

Contains almost 3 million litres of propellant, enough to power the engines for eight minutes.

4 ORION STAGE ADAPTER

Where small satellites are stored ahead of delivery to deep space.

5 ORION SPACECRAFT

The living quarters for the astronauts that will fly on future Artemis missions.

6 INTERIM CRYOGENIC PROPULSION STAGE

The juice needed for the final push towards the Moon once Artemis 1 leaves Earth orbit.

© NASA



THE ARTEMIS 1 FLIGHT PLAN

Artemis 1 will take a highly detailed and complex loop around the Moon and then come back to Earth

1 TRANS-LUNAR INJECTION BURN

After entering Earth orbit, rockets will fire for 20 minutes to send the spacecraft towards the Moon.

2 INTERIM CRYOGENIC PROPULSION STAGE

Once this has separated from the main spacecraft, there's no turning back.

3 LUNAR ORBIT INSERTION

Artemis 1 will use the Moon's gravity to slingshot out to a distant lunar orbit.

4 HEADING HOME

Artemis 1 will swing back down towards the lunar surface to help slingshot it home.

5 RETURN TRAJECTORY CORRECTION

The spacecraft's course will be tweaked through rocket burns to aim for Earth.

6 FINAL RETURN TRAJECTORY CORRECTION BURN

Final preparations to make sure the spacecraft hits the atmosphere at the right angle.

© Adrian Mann



© NASA

Left: A motor that's part of the Launch Abort System on Orion undergoes hot-fire testing in 2019

But pulling this off requires an entirely new launch system – and a bit of practice. At the time of going to press, November 2022 will hopefully have seen the delayed launch of Artemis 1, an uncrewed test flight. It will be the maiden use of NASA's Space Launch System (SLS), a powerful rocket that will send the new Orion Multi-Purpose Crew Vehicle (MPCV) on a 380,000-kilometre (236,120-mile) journey to the Moon. If all goes to plan then it will be followed by a crewed mission, Artemis 2, in 2024. It will test everything out in Earth orbit, then it's full steam ahead for the history-making Artemis 3 crew to land on the lunar south pole and spend a week there in 2025.

Even without a crew, Artemis 1 will be a record breaker. "Orion will stay in space longer than any ship for astronauts has done without docking to a space station and return home faster and hotter than ever before," says NASA. But first it has to leave Earth. Two huge boosters and a core stage filled with near 3 million litres of propellant will power the rocket through Earth's atmosphere. Once in space, the boosters will be jettisoned and the core stage will separate from the Orion spacecraft atop it. Orion will then orbit the planet while it deploys its solar panels. Finally, the Interim Cryogenic Propulsion Stage (ICPS) will fire to eject Orion from orbit and send it on its way.

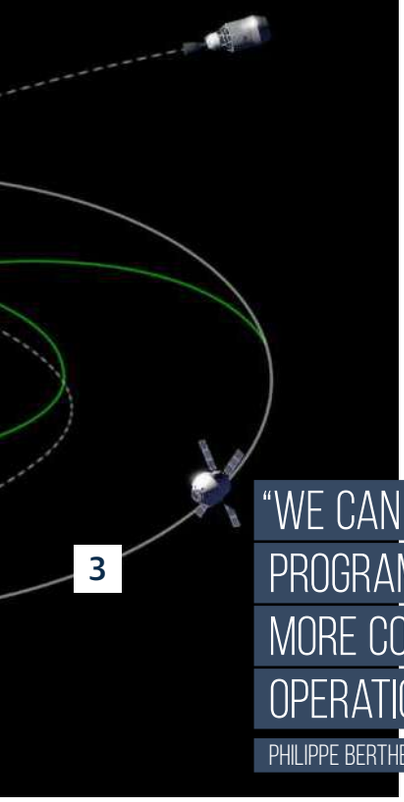
Once the ICPS has been discarded it has another job: to deploy a series of tiny satellites that have hitchhiked along for the ride. They include BioSentinel, a mission that will carry yeast samples beyond LEO. The idea is to study radiation levels and their effect on living organisms, providing key insights into keeping astronauts safe when they fly on Artemis 3. After separation from the ICPS, Orion will be propelled and powered by the European Service Module, built by the



© NASA

Left: Once completed, Gateway will be like an International Space Station in orbit around the Moon

Right: The Artemis 1 Flight Control Team simulating mission scenarios at Johnson Space Center in Houston



3

"WE CAN PROGRAM MUCH MORE COMPLEX OPERATIONS NOW"

PHILIPPE BERTHE

European Space Agency (ESA). "The Service Module will also provide consumables for future crew, including water and oxygen," says Philippe Berthe, the ESA's project coordination manager for the module.

Artemis 1 may not have a human crew on board, but the commander's seat will be occupied by a mannequin dressed in the Orion Crew Survival System – a special suit designed to help protect against radiation. Two radiation sensors will monitor radiation levels. The mannequin will be strapped in, but the weightless environment also needs testing, so NASA is flying a zero-gravity indicator in the form of a Snoopy cuddly toy dressed in an iconic orange NASA jumpsuit. The comic strip character has a long association with lunar exploration – the crew of Apollo 10 used it as a nickname for their Lunar Module.

So how does the new Service Module compare to the Lunar Modules that sent Apollo astronauts to the Moon? "The propulsion is largely the same; it's very comparable to the Apollo era," says Berthe. Yet half a century of technological progress has brought other strides forward. "There have been vast improvements in solar cells," Berthe explains, so that's where the spacecraft will derive most of its power. "Computing power is another major improvement," says Berthe. The Apollo astronauts famously flew to the Moon with less computing power than can be found in an iPhone. That meant a lot of manual tasks for the crew. This time around, the spacecraft's powerful computers can do most of the heavy lifting. "We can program much more complex operations now. The crew don't need to intervene directly in every nitty-gritty detail," Berthe says.

Artemis 1 will be gone for between 26 and 42 days. It'll take one or two weeks to get to the Moon, where it will swoop down close to the lunar surface and use the gravitational kick it receives to enter a so-called 'distant retrograde orbit'. Retrograde means that it will orbit the Moon in the opposite direction to that in which the Moon spins. It will stay in that orbit for between 6 and 19 days, and then it will swing back down towards the Moon for another kick to help power its 9 to 19 day journey back to Earth.

This project has been a labour of love for Berthe, who has been involved with it for nearly two decades and has seen many obstacles come and go. "One of the biggest challenges has been maintaining support across four administrations," he says. Presidents Bush, Obama, Trump and Biden have all wanted to put their spin on it and whether they wanted to go to the Moon or Mars. The timeline has also moved around, from a landing in 2028, then 2024 and now 2025. "The mission has changed a lot of times," Berthe says.

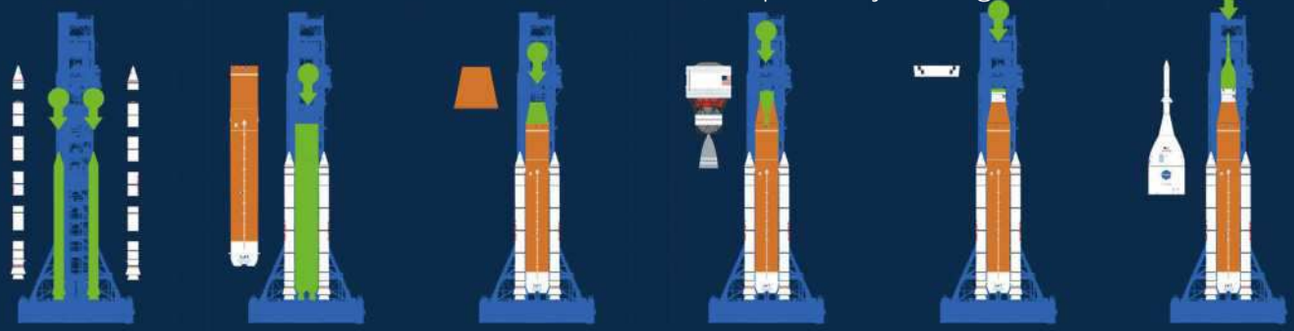
On top of the politics came the coronavirus pandemic, although Berthe says it didn't have as big an impact as he feared. "It was difficult for



© NASA

STACKING THE ROCKET

Before it can launch, the parts are joined together



1 SOLID ROCKET BOOSTERS
The boosters are added first. Each one has five segments stacked on top of each other.

2 CORE STAGE
The rocket's huge core stage is then placed between the two rocket boosters.

3 LAUNCH VEHICLE STAGE ADAPTER
The LVSA goes on top of the core stage to allow the rest of the bits to be added.

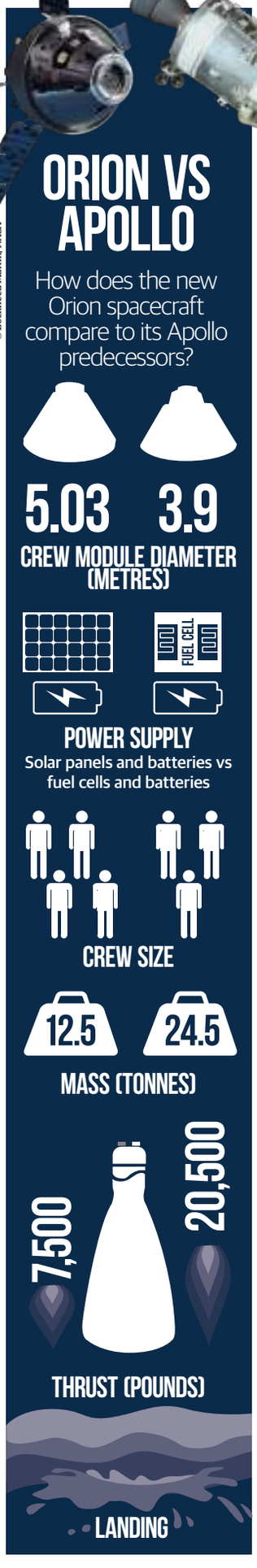
4 INTERIM CRYOGENIC PROPULSION STAGE
This is bolted into the top of the Launch Vehicle Stage Adapter.

5 ORION STAGE ADAPTER
This piece is specific to the spacecraft being used and is used to mate it to the rocket.

6 ORION SPACECRAFT
The preassembled Orion spacecraft, which carries the crew, is the last piece of the puzzle.

© NASA





© Lockheed Martin; NASA

people to cross international borders," he says. For a huge multi-agency project like this, that "somewhat slowed us down". There are also plenty of naysayers – those who argue that sending humans back to the Moon is a waste of time, money and resources. We've already done it, so why go back? Especially as we've already sent an armada of robotic spacecraft to both scan the Moon from orbit and drive across its surface. "An astronaut will do in six hours what a robot can do in six months," Berthe says. "It's more expensive, but it's more efficient."

We ultimately also want more than just fleeting visits. "We want to stay permanently and build something sustainable for the long run," Berthe says. To this end, an orbital outpost called Gateway is a big part of the Artemis program. Think of it like an International Space Station, but in orbit around the Moon – a home considerably further away from home. It could be ready as soon as November 2024 and it is intended to last for 15 years. The hope is that it will be ready in time for the crew of Artemis 3 to dock with.

While aboard Gateway, astronauts will stay in the Habitation and Logistics Outpost (HALO). There are also additional docking ports for cargo ships to come and go with supplies. Astronauts would then transfer to the Starship Human Landing System (HLS), a lunar lander based on SpaceX's existing Starship. However, if Gateway isn't ready then the crew will transfer directly to the HLS for landing at Artemis Base Camp.

Initially, stays will be short and largely inside the lander, but ultimately NASA wants astronauts living on the lunar surface for at least a month at a time in purpose-built accommodation. In September 2021 the agency put out a call for companies to submit their proposals for the next generation of spacesuits that Artemis astronauts will wear during their history-making moonwalks.

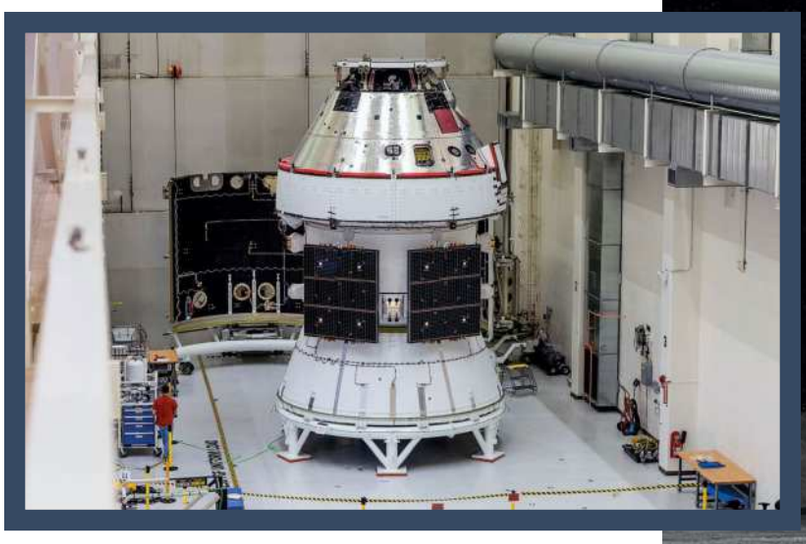
Eventually, the space between Earth and the Moon could be swarming with spacecraft ferrying goods and astronauts back and forth. Jeff Bezos, the founder of Amazon and CEO of space travel company Blue Origin, has suggested that the Moon could be a place to put our heavy industry, the idea being that it would free up living space on Earth and move our atmosphere-polluting infrastructure somewhere where there isn't even an atmosphere.

The Moon is also an ideal staging post for deeper Solar System exploration. The size and scale of the SLS shows just how hard we have to work to escape from Earth's gravitational clutches. The Moon's gravity, which is six times weaker than ours, is considerably easier to flee from. As past missions have discovered, there's also a huge amount of water on the Moon. As water is H_2O, that means an abundant supply of oxygen. In fact, the Moon's top layer alone has enough oxygen to sustain 8 billion people for 100,000 years.

Liquid oxygen is also rocket propellant. That's why Artemis Base Camp will be at the Moon's south pole. We already know that there's plenty



Below: The Orion spacecraft being prepared at Kennedy Space Center in Florida



©NASA

of water there. Lunar Flashlight, one of the small spacecraft hitching a ride on Artemis 1, will orbit the Moon and shine infrared lasers into permanently shadowed craters near the lunar poles to further reveal the quantity and quality of water ice there. The sunlight at the south pole is also favourable – it's illuminated approximately 90 per cent of the time, compared to two weeks of daylight followed by two weeks of darkness on the rest of the Moon. That's good news for a colony powered by solar panels. The combination of these two factors may lead to a time when rocket ships routinely fuel up close to Artemis Base Camp and blast off for more distant destinations, such as Mars and the asteroid belt.

Former NASA administrator Jim Bridenstine certainly sees lunar exploration as a key step on our journey towards becoming an interplanetary species. He has said that "we need several years in orbit and on the surface of the Moon to build operational confidence for conducting long-term work and supporting life away from Earth before we can embark on the first multi-year human mission to Mars".

It's all part of returning to where we came from. The iron in your blood and the calcium in your bones was forged inside stars that blasted them across the universe when they died. Eventually those atoms found themselves inside sentient creatures who dreamed of sailing between the stars and built cathedral-sized rocket ships to take them there. The Artemis 1 launch later this year may only be a small step, but it's an important one. Future historians could look back on it as the moment humanity took a giant leap in its return to the Moon, this time for good.



Colin Stuart
Science author and speaker
Colin holds a degree in astrophysics, has written over 17 books on space and has an asteroid named in his honour: 15347 Colinstuart.

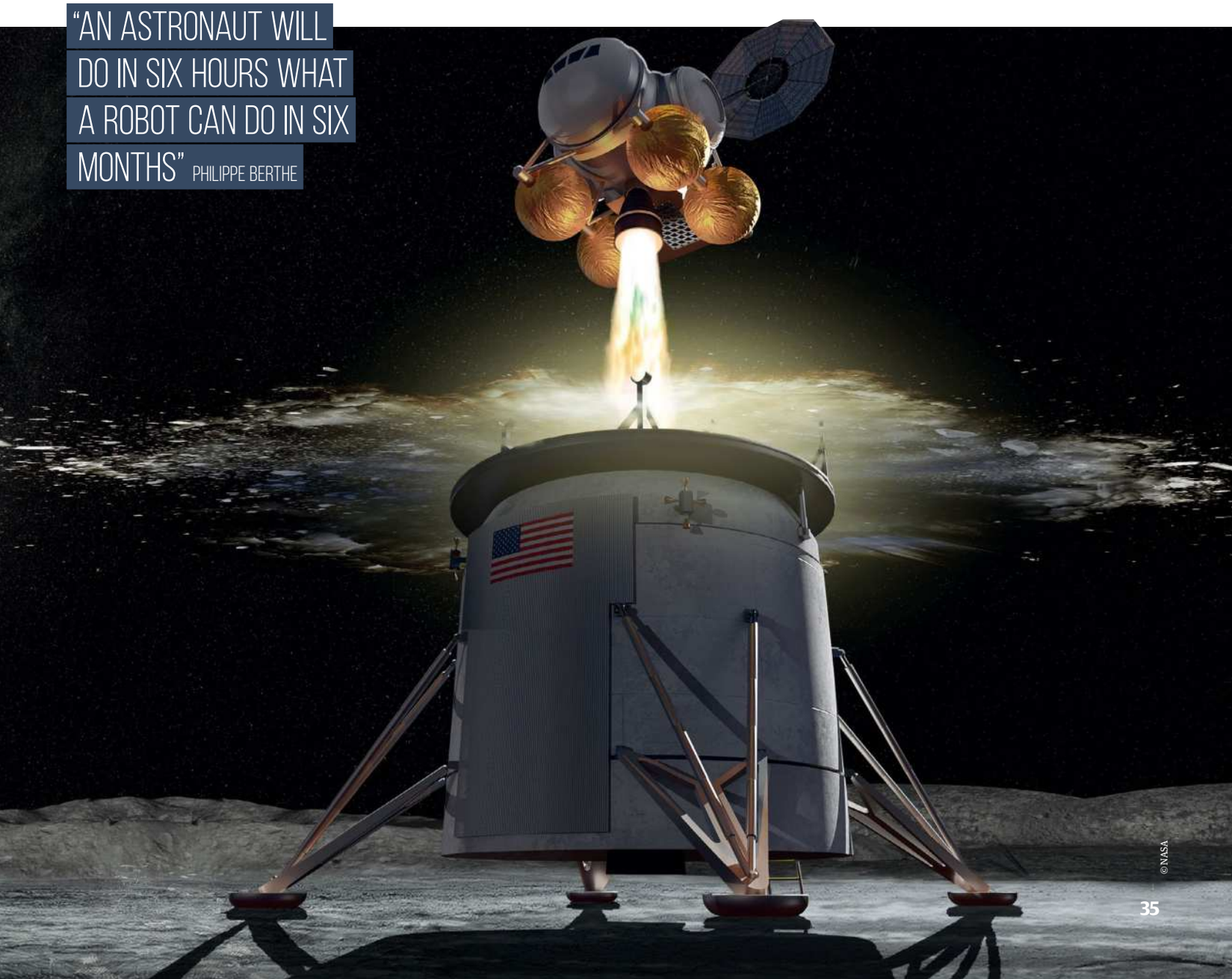
Right: An Orion spacecraft witnessing Earthrise over the craggy lunar surface

Below: Artist's impression of an ascent vehicle beginning the journey back to Earth



© NASA

"AN ASTRONAUT WILL DO IN SIX HOURS WHAT A ROBOT CAN DO IN SIX MONTHS" PHILIPPE BERTHE



© NASA

COLD, DAMP MARS MAY HAVE HOSTED AN ANCIENT OCEAN

Northern parts of the Red Planet could have supported bodies of liquid 3 billion years ago



Reported by Charles Q. Choi

New 3D climate simulations of the planet's ancient atmosphere and water suggest a liquid ocean once existed in the northern lowland basin of Mars. This ocean may have persisted even when average global surface temperatures were below freezing. Although present-day Mars is cold and dry, decades of evidence suggests the ancient surface was covered with rivers, streams and lakes. Since water on Earth usually points to life, these old signs of water raise the possibility that the Red Planet was once home to life.

Earth and Mars likely had similar climates about 3 billion years ago, when life was spreading on our planet. However, scientists debate whether Mars was temperate enough to host an ocean of water. NASA's Perseverance rover is one of many missions sent to Mars to assess the planet's suitability for hosting ancient water.

The new findings contradict previous research suggesting Mars couldn't support such an ocean 3 billion years ago. Relatively few branching river valleys date to that time on Mars, suggesting a lack of intense and widespread rainfall expected from a warm and wet climate. But not all evidence points to a dry world; other evidence of contemporary tsunami debris argues against a Martian climate that was too cold and dry for an ocean. The new study suggests a liquid northern ocean was possible because ocean circulation patterns may have warmed up the surface of that region up to 4.5 degrees Celsius (40.1 degrees Fahrenheit), well above water's freezing point.

More water was possibly in ample supply, too. The northern ocean could have experienced moderate rainfall within it, as well as near its shorelines. Another potential source was flowing glaciers from the southern highlands of the Red Planet, which hosted ice sheets.

An ocean-friendly Martian atmosphere looks somewhat like the carbon dioxide-filled version we see today, but with a twist: roughly ten per cent of the atmosphere was made up of ten per cent hydrogen gas, potentially being released by volcanoes, cosmic impacts or chemical interactions between water and rock. Today, by contrast, hydrogen is only present in trace amounts. This combination of carbon dioxide and hydrogen could have trapped enough heat from the Sun to keep surface temperatures warm enough for an ocean of liquid water.

It remains uncertain, however, whether this ocean could have supported life. "We are only studying the conditions where life could appear," study lead author Frédéric Schmidt, a planetary scientist at the University of Paris-Saclay, said. "A large standing body of water stable for a long time is important, probably necessary, but maybe not sufficient for life to appear." Scientists are also unsure where the water went, Schmidt noted. Much of it could be frozen as ice under the surface of Mars, or chemically locked away in minerals. Solar radiation may have also broken water molecules apart into hydrogen and oxygen gases, with the hydrogen gas ultimately escaping into space, he added. NASA is currently tracking present-day Red Planet gas emissions through missions such as MAVEN (Mars Atmosphere and Volatile Evolution).

In the future, China's Zhurong rover – along with the planned ExoMars Rosalind Franklin rover from the European Space Agency and Russia's Roscosmos – could analyse the proposed boundary of this ancient ocean to confirm whether there are a shoreline and tsunami deposits there, the scientists said. In the longer term, the proposed International-Mars Ice Mapper mission could uncover additional signs of ancient seas on Mars. Future research may also explore what exact paths glaciers took to reach this ocean to assist scientists in mapping geological evidence of glacial routes. "For the moment, our simulation cannot predict that," Schmidt said.

> "THE NORTHERN OCEAN COULD HAVE EXPERIENCED MODERATE RAINFALL WITHIN IT"

© Getty



Above: The Red Planet today is a dry and desolate desert world

MISSION PROFILE

LUCY

NASA's Lucy mission is headed to the Trojan asteroids in search of cosmic fossils

Mission type
Multiple flyby
Operator
NASA
Launch date
16 October 2021
Target
Trojan asteroids
Arrival at target
2027
Primary objective
To explore one main-belt asteroid and seven Trojan asteroids
Status
In progress



© NASA

Harold 'Hal' Levison
Lucy principal investigator
The Lucy mission is led by principal investigator Harold 'Hal' Levison from the Southwest Research Institute in Boulder, Colorado. He specialises in the formation and long-term behaviour of Solar System bodies, including comets, Kuiper belt objects and the Trojan asteroids.

Lucy is a NASA probe that launched on 16 October 2021. It will be the first-ever mission to explore a set of asteroids near Jupiter known as the Trojan asteroids. These ancient space rocks hold important clues to the creation of our Solar System and possibly the origin of life on Earth.

Along with a mission called Psyche, Lucy was approved in January 2017 as part of NASA's Discovery program, which supports focused and relatively cheap planetary missions whose development costs are capped at around $450 million (£328 million). A year after approval, the mission was officially given a schedule and a set of eight asteroid targets. Lucy is named for a famous female *Australopithecus afarensis* fossil found in Ethiopia that, as a relative of modern humans, helped illuminate the evolution of our species. It's hoped that the spacecraft will similarly elucidate our Solar System's earliest days.

Lucy spans more than 14 metres (46 feet) from tip to tip – larger than a four-storey building – though much of that will be the enormous solar panels used to power the spacecraft. The spacecraft will carry an instrument that can measure the surface temperatures of its target asteroids and provide information about their composition, two high-resolution cameras and a device that uses infrared light to inspect and identify ice, organic material and different minerals in each asteroid.

NASA launched Lucy on its planned 12-year mission on an Atlas V 401 rocket from Cape Canaveral in Florida. The total cost to launch the spacecraft was approximately $148.3 million (£108 million), which includes the launch service and other mission-related costs.

The probe's main objects of study are the Trojan asteroids. These objects are thought to be remnants from the primordial disc that formed the Sun and planets, captured by Jupiter's immense gravity soon after the gas giant's formation. Lucy will be the first mission to visit the Trojans, which are all named for famous figures from the Trojan war in Greek mythology. The Trojans share Jupiter's orbit around the Sun in two loose groups, with one set slightly ahead of the gas giant and another trailing behind it. The Trojans are stabilised by the Sun and its largest planet in a gravitational balancing act, keeping them in the same path.

After being launched from Earth, the spacecraft will first make a quick flyby of a main-belt asteroid in 2025. The small, rocky target is named 52246 Donaldjohanson after the palaeontologist who discovered the Lucy fossil. Situated between Mars and Jupiter, the flyby will serve primarily as a test for the spacecraft's instruments.

If all goes according to plan, between 2027 and 2033 Lucy will go on to fly past seven Trojan asteroids, including three different asteroid subclasses and two objects that rotate around each other. NASA has stated that "no other space mission in history has been launched to as many different destinations in independent orbits around our Sun". The mission's targets include C-type, D-type and P-type asteroids, each of which will help scientists better understand the Solar System's genesis.

During the 12-year mission, Lucy will travel almost 6.4 billion kilometres (4 billion miles) and will make three-and-a-half loops around the Sun. Remarkably, Lucy will travel out past Jupiter and then loop back to the vicinity of Earth for a final gravity assist that will send the spacecraft out to its final Trojan encounters. Lucy will perform these manoeuvres at average speeds of 643,737 kilometres (400,000 miles) per hour.

Lucy will also carry a mission plaque similar to those found on Pioneer 10 and 11 and the Golden Records on Voyager 1 and 2. The plaque features messages from individuals asked to provide words of wisdom, joy and inspiration to those who may read the plaque in the future. This cosmic time capsule features messages from world-renowned poets and artists, including Charles Simic, Rita Dove, Billy Collins and Beatles drummer-vocalist Ringo Starr to name but a few.

LUCY'S KIT

SPECIFICATIONS

Height: 7.2 metres (23.6 feet)

Width: 14.2 metres (46.6 feet)

Depth: 2.8 metres (9.2 feet)

Solar panel diameter: 7.3 metres (24 feet)

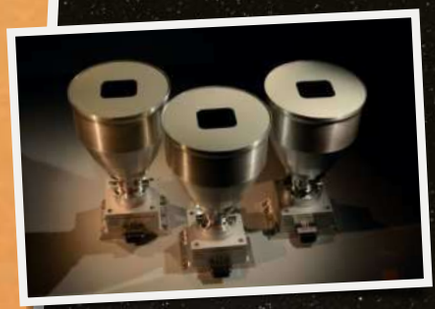
Launch mass: 1,550 kilograms, including fuel

HIGH-GAIN ANTENNA

This large two-metre (6.5-foot) antenna will beam back close-up images of the Trojan asteroids. The signal will also help scientists determine the mass of the asteroids by measuring changes in frequency caused by the Doppler effect.

TERMINAL TRACKING CAMERAS (T2CAM)

These tracking cameras will not only keep track of the asteroids during Lucy's encounters, but will also provide wide-field images of the targets to help scientists get a better idea of their shape.



© NASA



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WHAT ARE C-TYPE ASTEROIDS?

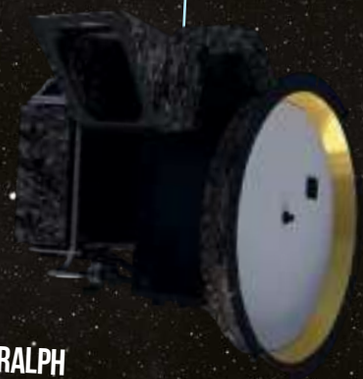
Lucy will fly past two C-type, or carbonaceous, asteroids: the main asteroid belt object Donaldjohanson and a Trojan named Eurybates.

C-type asteroids are rich in carbon and are where most meteorites on Earth originated from. The OSIRIS-REx and Hayabusa2 missions have previously collected samples from C-type asteroids to bring back to our planet for study.

WHAT ARE D-TYPE AND P-TYPE ASTEROIDS?

Lucy will also inspect two D-type asteroids, which are named Leucus and Orus, and three P-type asteroids, one named Polymele and a binary asteroid pair orbiting one another called Patroclus and Menoetius.

D-type and P-type asteroids appear much redder than C-type asteroids and are hypothesised to be rich in organic and volatile elements. No mission has ever flown past a D-type or P-type asteroid before.



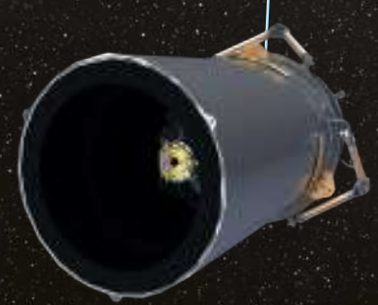
L'RALPH

This two-in-one instrument contains Lucy's colour camera, the Multispectral Visible Imaging Camera (MVIC) and the infrared-imaging Linear Etalon Imaging Spectral Array (LEISA) spectrometer, which will be used to find out what the asteroids are made from.



L'TES

The infrared Thermal Emission Spectrometer will remotely measure the surface temperatures of the target asteroids.



L'LORRI

The Long Range Reconnaissance Imager will capture high-resolution black-and-white images of the target asteroids. According to the Southwest Research Institute (SwRI), it's affectionately known as the 'eagle eyes' of the mission.

x4 Image © Southwest Research Institute (SwRI)

MISSION PROFILE

MISSION OBJECTIVES



© Southwest Research Institute (SwRI)

Lucy aims to shed light on the history of our Solar System and explore the cosmic 'time-capsules' that are the Trojan asteroids, which may have been around since the birth of our Solar System over 4.5 billion years ago. Investigating this primordial material could even tell us about the kinds of materials that may have contributed to the early Earth. The asteroids are expected to provide a wealth of information, especially about the organic material that would have rained down on our planet in its earliest days, potentially helping to trigger the creation of living organisms. Each target is also thought to contain water ice underneath its rocky surface.

During the early Solar System, the primitive bodies that eventually formed into planets were compositionally diverse – as are the Trojan asteroids. To understand the diversity of the Trojan asteroids, Lucy will attempt to find out how old the asteroids are, as well as mapping their shape and the albedo of their surfaces. Lucy will also investigate the size and spatial distribution of craters on the target asteroids.

To find out what the asteroids are made of – including the distribution of minerals and ice – Lucy will map the colour and composition of the asteroids' surfaces using its myriad of specialised scientific instruments.

Lucy will measure the mass and density of the target asteroids and remotely investigate their interior properties. Lucy will be able to study the subsurface composition by observing material brought up to the surface through impact craters and fractures in the asteroids. Lucy will also keep an eye out for satellites and rings that might orbit the targeted Trojan asteroids, such as Queta that orbits Eurybates.



© NASA/JPL-Caltech

Above: The massive solar arrays make up the bulk of the spacecraft and will provide it with power

Left: Some Trojans follow in Jupiter's path, while others orbit ahead of the gas giant

LUCY IN THE SKY WITH DIAMONDS... AND TROJANS



"EACH TARGET IS ALSO THOUGHT TO CONTAIN WATER ICE UNDERNEATH ITS ROCKY SURFACE"

LUCY'S TARGETS

Lucy will have an 'opportunistic trajectory' – one dictated by celestial mechanics so that a single spacecraft can reach a record number of asteroids for observation. Once Lucy has visited all eight targets, it will continue to cycle between the two Trojan asteroid groups every six years. Lucy's orbit will eventually become unstable, and it's likely Jupiter's gravity will cause the spacecraft to either be catapulted into the Sun or flung out of the Solar System.

x8 Images © NASA

52246 DONALDJOHANSON

Estimated diameter: 3.8 kilometres (2.4 miles)

A main-belt C-type asteroid located between Mars and Jupiter, scientists will test Lucy's instruments on this target before heading to the Trojans.



3548 EURYBATES

Estimated diameter: 68 kilometres (42 miles)

Eurybates will be Lucy's first Trojan target. The C-type asteroid is a giant remnant of a massive collision.

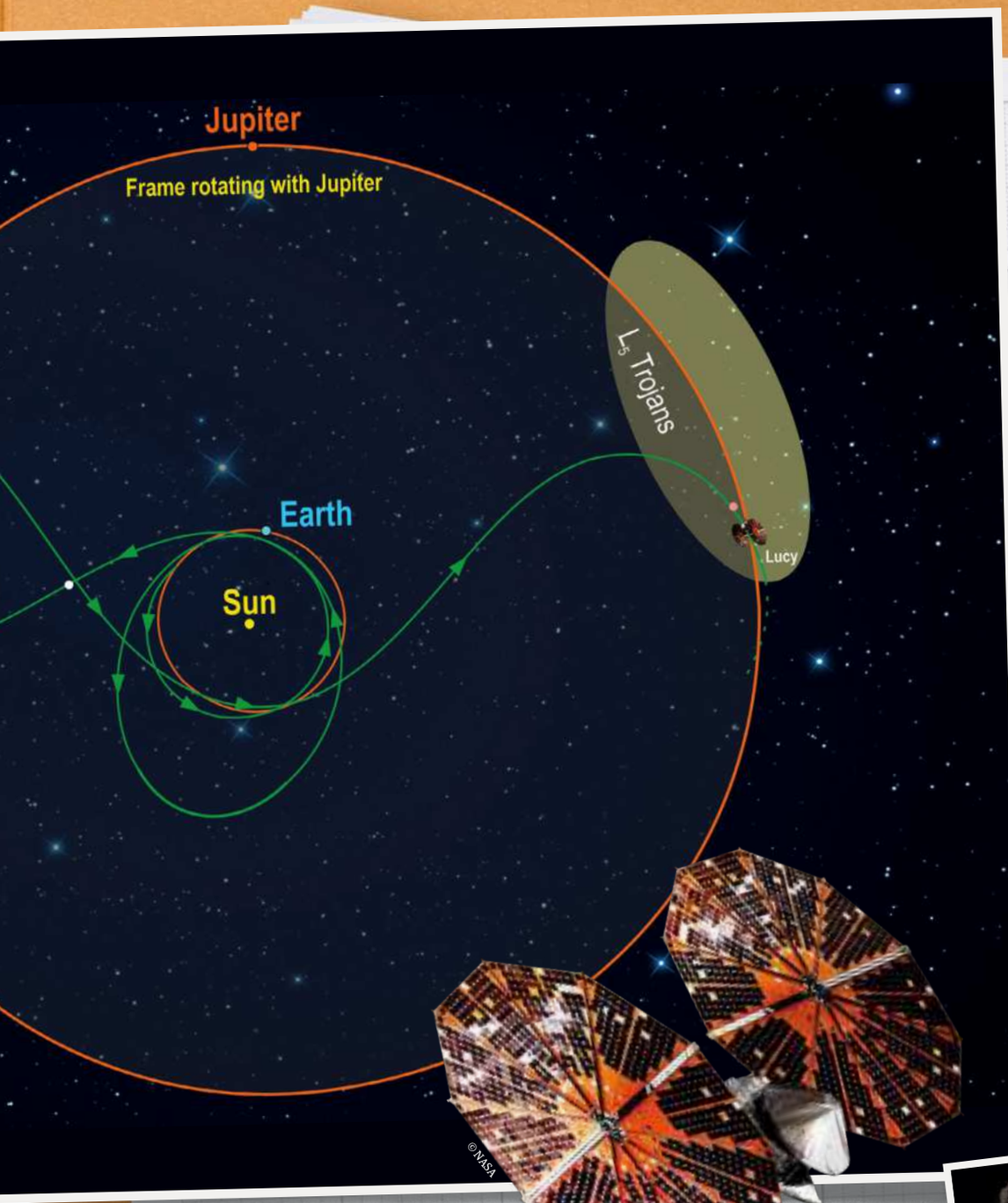


QUETA

Estimated diameter: One kilometre (0.6 miles)

Queta orbits Eurybates. On 9 January 2020 the mission team announced Lucy will be visiting this eighth target after discovering it.





© NASA

FLYBY TIMELINE

16 OCTOBER 2021
Lucy launched aboard an Atlas V 401 rocket from Cape Canaveral in Florida.

20 APRIL 2025
Lucy will observe its first and only asteroid in the main asteroid belt, Donaldjohanson.

12 AUGUST 2027
Lucy will observe Eurybates and its satellite Queta.

15 SEPTEMBER 2027
Lucy will observe Polymele.

18 APRIL 2028
Lucy will observe Leucus.

11 NOVEMBER 2028
Lucy will observe Orus before heading back towards Earth, then out towards Jupiter and the trailing L5 swarm.

26 DECEMBER 2031
Lucy will perform another Earth flyby, preparing the craft for its journey to the two remaining target asteroids.

2 MARCH 2033
Lucy will observe the binary pair Patroclus and Menoetius, marking the final flyby.

© Southwest Research Institute (SwRI)



15094 POLYMELE
Estimated diameter: 21 kilometres (13 miles)
Lucy will attempt to fly within 399 kilometres (248 miles) of this P-type asteroid. It will be the first time a craft has ever flown by this class.



11351 LEUCUS
Estimated diameter: 40 kilometres (25 miles)
A D-type, it takes 446 hours to make a single rotation. The slow rotation means that Leucus likely gets hotter during the day and colder at night.



21900 ORUS
Estimated diameter: 51 kilometres (32 miles)
This D-type asteroid will be compared to the smaller D-type asteroid Leucus, and also to the similarly sized C-type Eurybates.



PATROCLUS AND MENOETIUS
Estimated diameter: 113 kilometres (70 miles) and 104 kilometres (65 miles) respectively
P-type Patroclus and Menoetius are binary asteroids thought to be relics from the very early Solar System. Lucy's final encounter with Patroclus and Menoetius is considered particularly special because the pair spend most of their time orbiting high above the main ecliptic plane of the Solar System, and are therefore hard to reach. The elusive asteroid pair will be passing through a region that is accessible to Lucy in March of 2033, when the spacecraft is scheduled to reach them.

Focus on

PLUTO'S ATMOSPHERE IS STARTING TO DISAPPEAR

The dwarf's nitrogen-rich atmosphere is going through a strange transformation

Reported by Chelsea Gohd





© NASA

Left: Starlight from behind the dwarf highlighted its atmosphere

Main: Pluto's irregular orbital path causes it to change temperature as it circles the Sun

The icy dwarf planet, which lies over 4.8 billion kilometres (3 billion miles) away from Earth in the Kuiper Belt, caught astronomers' attention as it passed in front of a star back in 2018.

With the star backlighting Pluto, a team of researchers was able to make observations of the dwarf planet and its atmosphere. With this unique view, they came to a surprising conclusion: they found evidence that Pluto's atmosphere is starting to disappear.

Using telescopes at multiple sites in both the US and Mexico, the team observed Pluto and its thin atmosphere, which is primarily made of nitrogen. Pluto's atmosphere is supported by the vapour pressure of ices on the dwarf planet's surface; if ice warms up on Pluto, it can dramatically alter the density of its atmosphere.

For about 25 years, Pluto has been moving farther and farther away from the Sun, so its surface temperature has been going down. And with these recent observations, the researchers found evidence showing that Pluto's atmosphere is actually refreezing back onto its surface as the dwarf planet gets colder and colder. Pluto is so far from the Sun that as time goes on it will get distinctly farther away before getting closer to the Sun in other regions of its immense orbit.

Thanks to a phenomenon known as thermal inertia, Pluto's surface pressure and atmospheric density continued to rise until 2018. Essentially, Pluto had residual heat from when it was closer to the Sun. However, the inertia is starting to wear off, and as Pluto gets colder, more and more of its atmosphere will freeze back onto its surface and 'disappear'.

"An analogy to this is the way the Sun heats up sand on a beach," said Southwest Research Institute (SwRI) staff scientist Leslie Young, who studies the interaction between icy Solar System bodies and their surfaces and atmospheres.

"Sunlight is most intense at high noon, but the sand then continues soaking up the heat over the course of the afternoon, so it's hottest in the late afternoon. The continued persistence of Pluto's atmosphere suggests that nitrogen ice reservoirs on Pluto's surface were kept warm by stored heat under the surface. The new data suggests they are starting to cool," Young said.

The researchers watched the star fade as Pluto moved in front of it and then come back into view once the dwarf planet had passed. Using the rate that the star came in and out of view – a transition that lasted about two minutes – they were able to determine the density of the dwarf planet's atmosphere.

This method relies on what is known as an 'occultation' – when one cosmic object is hidden by another passing in front of it. Studying occultations is an old and well-worn technique in the world of astronomy, and researchers have used it to study Pluto's atmosphere since 1988, Eliot Young, a SwRI senior program manager, said.

"New Horizons obtained an excellent density profile from its 2015 flyby, consistent with Pluto's bulk atmosphere doubling every decade, but our 2018 observations don't show that trend continuing from 2015," Young added.

In observing Pluto as it passed in front of the star, the team noticed a 'central flash' in the middle of the path of the dwarf planet's shadow. The flash, caused by Pluto's atmosphere refracting light into the centre of the shadow, changed the light curve that usually happens during occultation from a U shape into a W.

"The central flash seen in 2018 was by far the strongest that anyone has ever seen in a Pluto occultation," said Young. "The central flash gives us very accurate knowledge of Pluto's shadow path on Earth."

"NITROGEN ICE RESERVOIRS ON PLUTO'S SURFACE WERE KEPT WARM BY STORED HEAT" LESLIE YOUNG

© Getty

LARGEST COMET EVER DISCOVERED IS HEADED OUR WAY

Bernardinelli-Bernstein is making its trip towards the Sun

Reported by Brandon Specktor

An enormous comet – possibly the largest one ever detected – is barrelling towards the inner Solar System with an estimated arrival time of ten years from now.

The comet, known as Bernardinelli-Bernstein, or officially C/2014 UN271, is at least 100 kilometres (62 miles) across – about 1,000 times more massive than a typical comet. It's so large that astronomers previously mistook it for a dwarf planet.

A closer analysis of the object revealed that it was moving rapidly through the Oort Cloud – a vast scrap yard of icy rocks billions of miles from Earth. The object appeared to be headed our way, and it even had a glowing tail, or 'coma', behind it – a clear indication of an icy comet approaching the relatively warm inner Solar System. Now researchers have studied the massive comet in more detail, and they have new estimates about its journey towards the Sun.

For starters, the enormous rock poses no threat to Earth. Right now Bernardinelli-Bernstein (BB) is cruising through the Oort Cloud at about 29 times the distance between Earth and the Sun, or 29 astronomical units (AU). The comet's closest approach to Earth will occur some time in the year 2031, when scientists predict the comet will swoop within 10.97 AU of the Sun – putting it just outside of Saturn's orbit.

While that's far enough from Earth that observers won't be able to see the comet without telescopes, it's considerably closer than the rock's last visit to our part of the Solar System. After modelling the comet's trajectory, new research calculated that BB made its last approach 3.5 million years ago, coming within 18 AU of the Sun. Since then, the comet travelled as far as 40,000 AU away, deep into the mysterious Oort Cloud. "We conclude that BB is a 'new' comet in the sense that there is no evidence for [a] previous approach closer than 18 AU," the researchers wrote; in other words, humans have never laid eyes on it before.

We owe our current view of the large, distant comet to the Dark Energy Survey (DES) – a project to study the expansion of the universe

"RESEARCHERS HAVE PLENTY OF TIME TO STUDY THE MASSIVE COMET AS IT SOARS EVER CLOSER TO EARTH OVER THE NEXT DECADE"

Right: The object was originally thought to be a dwarf planet because of its size

©NOIRLab



which ran between August 2013 and January 2019. During the survey, astronomers mapped 300 million galaxies in the southern sky, discovering more than 800 previously unknown objects beyond the orbit of Neptune. The BB comet was one of those objects.

Researchers have plenty of time to study the massive comet as it soars ever closer to Earth over the next decade. Getting a closer look at the rock could help scientists understand a bit more about the chemical composition of the early Solar System, as comets from deep in the Oort Cloud are thought to be relatively unchanged since they were booted away from the Sun billions of years ago. With millions of years separating the comet's next close approach from its following one, it'll be a once-in-a-lifetime brush with the early Solar System.

DEEP SPACE

Go beyond the Solar System and uncover the mysteries of the universe

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These behemoths might dwell far from galactic centres

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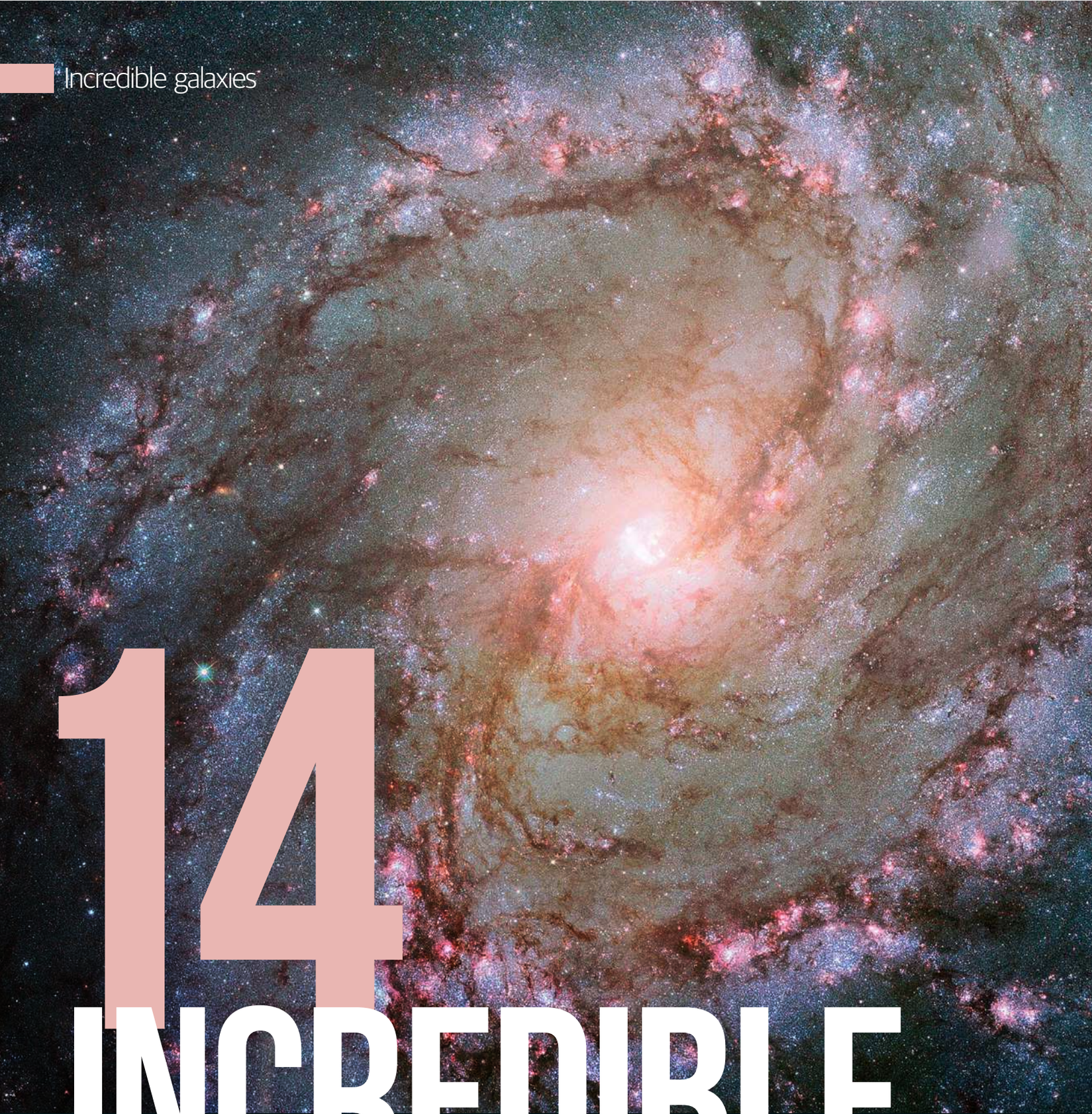
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14 INCREDIBLE GALAXIES

OUT BEYOND OUR MILKY WAY THERE ARE GALAXIES SHAPED LIKE JELLYFISH, GALAXIES THAT CONSUME OTHERS AND GALAXIES THAT SEEM TO LACK THE DARK MATTER THAT PERVADES THE REST OF THE UNIVERSE

Written by Stephanie Pappas

1 PRETTY PINWHEEL

MESSIER 83

Messier 83 is a large, photogenic spiral galaxy with a bar-shaped centre. It sits 15 million light years away in the constellation of Hydra. Messier 83 is weird in a couple of ways. First, it appears to have a double nucleus at its centre – perhaps the mark of two supermassive black holes holding the galaxy together, or perhaps the effect of a lopsided disc of stars orbiting a single central black hole. Secondly, Messier 83 is a supernova supersite. Astronomers have directly observed six of these stellar explosions in the galaxy, along with remnants of 300 more. This puts Messier 83 in second place for supernovae – only the galaxy NGC 6946 has produced more observable stellar explosions, with nine.



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2 TWO HEARTS

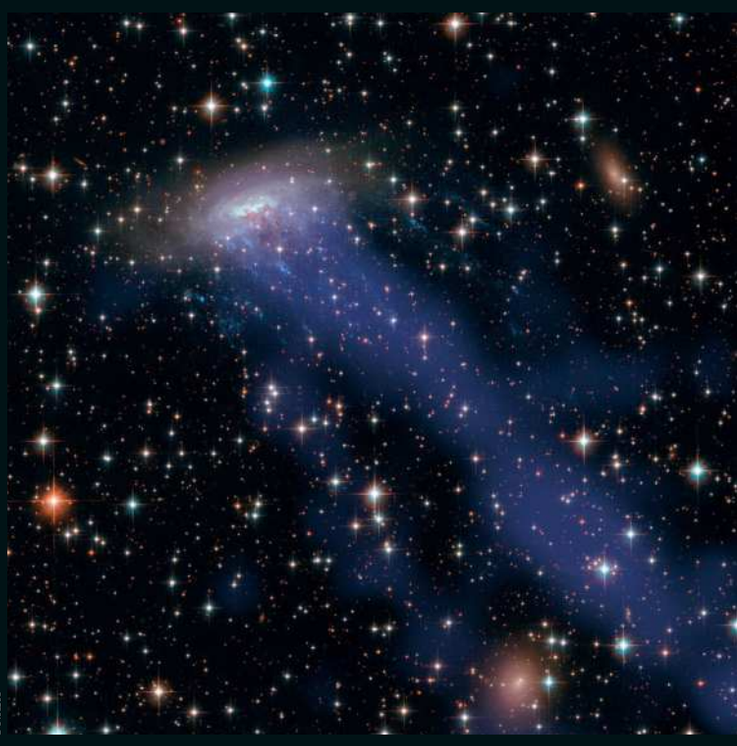
NGC 7674

Most galaxies are likely to be anchored by a supermassive black hole at their centre. A few, however, contain not one, but two black holes. One of these is NGC 7674, a spiral galaxy whose centre boasts a pair of black holes a mere light year apart. The galaxy, 380 million light years from Earth, probably collected the spare black hole during a collision and merger with another galaxy. The only other galaxy known to have two black holes at its heart is a supermassive galaxy called 4C +37.11.

3 JUST LIKE A JELLYFISH

ESO 137-001

Located in the constellation of Triangulum Australe, ESO 137-001 looks like a jellyfish swimming amid a sea of stars. The galaxy is a barred spiral – together its stars form a spiral shape with a bar-shaped centre – with a twist: streamers of stars that seem to drift like jellyfish tentacles. These stars are forming inside a tail of dust and gas – one invisible to the naked eye – that streams off ESO 137-001. This formation process is a bit of a mystery, as the gases in the tail should be too hot for star formation.



© NASA



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4 GALAXY IN BLOOM

ESO 381-12

Against the void of space, ESO 381-12 seems to bloom. This galaxy, 270 million light years from Earth, is in the constellation of Centaurus. It's a lenticular galaxy, a hybrid between a spiral galaxy and a stretched-out elliptical galaxy. What makes ESO 381-12 really strange are the uneven, petal-like blooms that ghost outwards from the main galactic body. Astronomers aren't entirely sure what causes these structures, or the clusters of stars that orbit on the galaxy's edges. It's possible that the blooms are shock waves from a relatively recent galactic collision that also provided the galaxy with new fuel for star formation.

5 LUMINOUS THIEF

W2246-0526

Galaxies frequently interact with one another, squeezing their neighbours into new shapes, stealing stars and carrying on with other shenanigans. The brightest known galaxy in the universe is one of these thieves. In 2018, scientists announced that they'd observed the galaxy W2246-0526 sucking up half the mass of three nearby galaxies. Astronomers were able to observe streamers of mass connecting the galaxies – at least as they were more than 12 billion years ago, when that light began its journey towards Earth.



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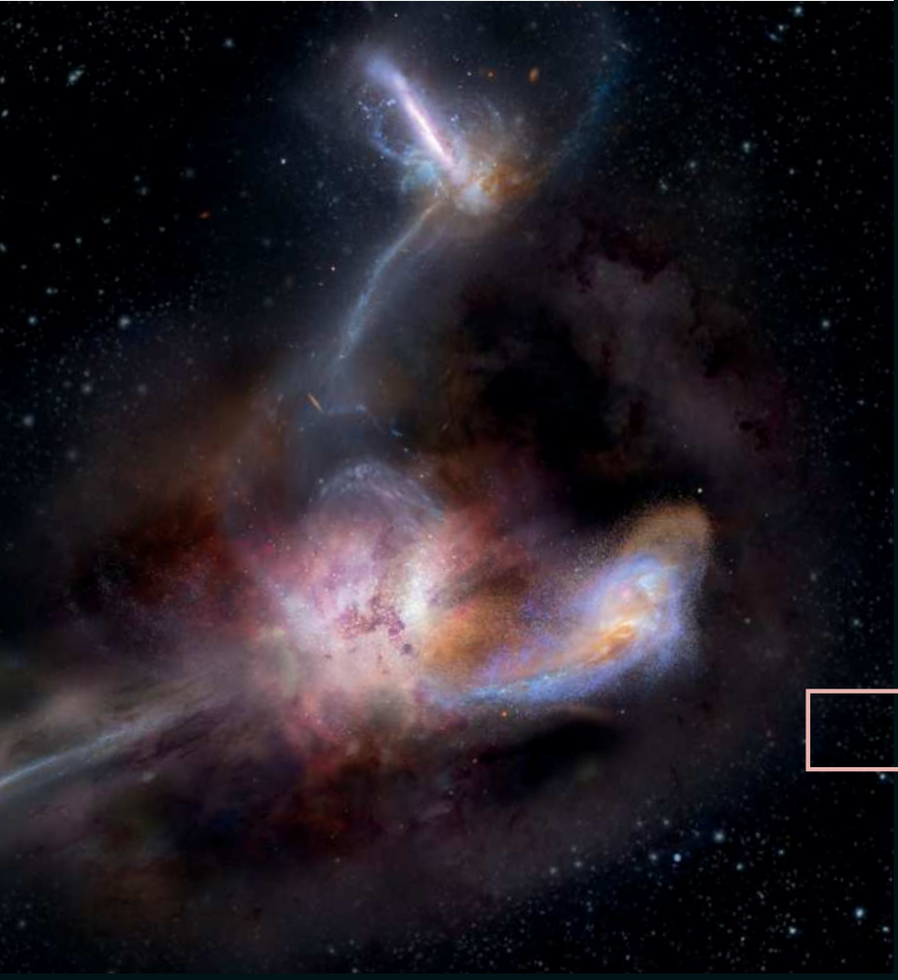
"WHAT MAKES ESO 381-12 REALLY STRANGE ARE THE UNEVEN, PETAL-LIKE BLOOMS THAT GHOST OUTWARDS FROM THE MAIN GALACTIC BODY"



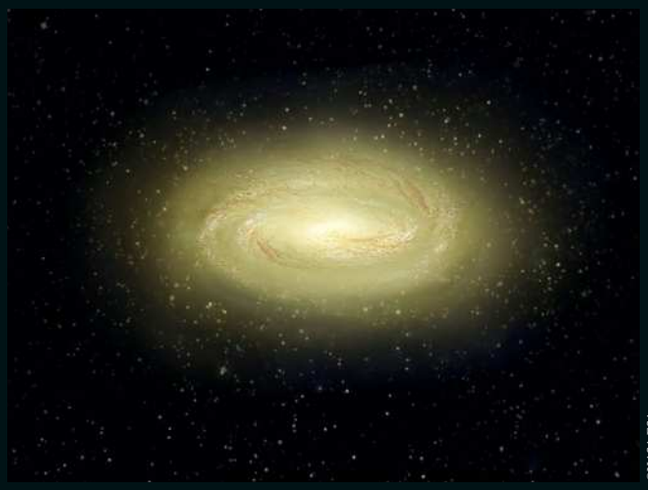
6 THE EYE

IC 2163 & NGC 2207

The disc of spiral galaxy IC 2163 seems to peer out into space with an enormous eye. This eye-shaped feature is actually a huge stream of stars and dust, produced when the smaller IC 2163 brushed against another spiral galaxy, NGC 2207. These 'ocular features' last only a few tens of millions of years – that's a blink of an eye in the life span of a galaxy, so discovering one is a unique opportunity. Researchers found that the gases of the eye race towards the centre of IC 2163 at 100 kilometres (62 miles) per second before crashing like a wave on the shore, becoming more chaotic and slowing as they move towards the centre.



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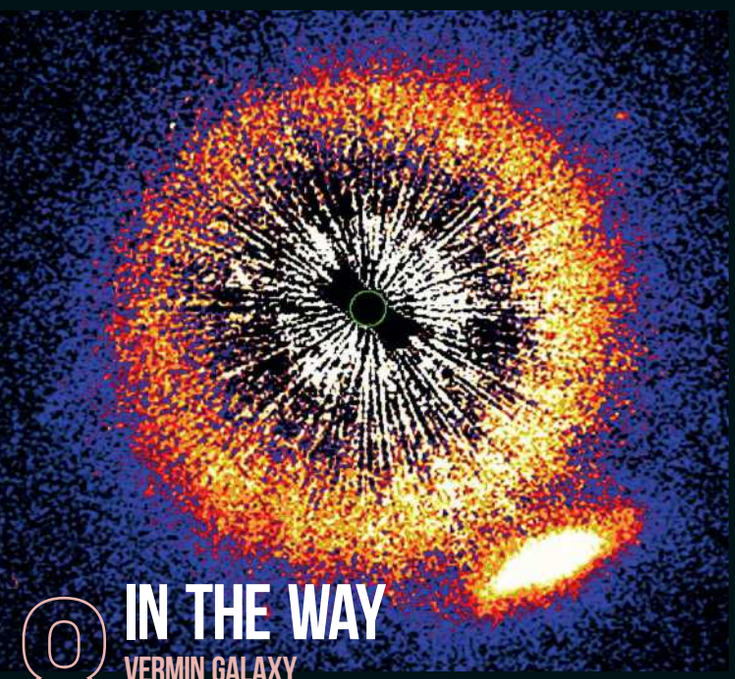


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7 ZOMBIE GALAXY

MACS 2129-1

The massive, disc-shaped MACS 2129-1 spins twice as fast as the Milky Way, but it's not nearly as active. Hubble observations of the distant galaxy reveal that it hasn't made stars for some 10 billion years. MACS 2129-1 is what's known as a dead galaxy; stars no longer form there. Its discovery was a head-scratcher. Scientists believed galaxies of this sort formed by merging with smaller galaxies over time, but its stars didn't form from these sorts of explosive mergers – they formed early on in the disc of the original galaxy. The findings suggest that dead galaxies somehow internally rearrange their structure as they age rather than changing shape because they combine with other galaxies.



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8 IN THE WAY

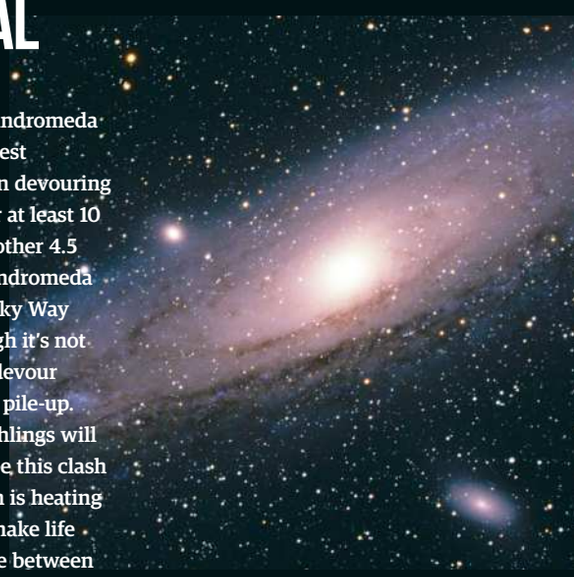
VERMIN GALAXY

This looks more like a psychedelic bit of dandelion puff than a cosmological phenomenon, but this snapshot captured by Hubble has nothing to do with botany. What you're seeing is a galaxy (the smudge at the lower right) beginning to pass behind a star (the sphere). Its called the 'Vermin Galaxy' by some because its light gets in the way of studying the closer star and its system. In 2020, the star fully obscured the galaxy, but scientists can study the spectra of light as the galaxy makes its transit behind the star, perhaps gleaning some information about the debris around the star from the light that makes its way through.

9 COSMIC CANNIBAL

ANDROMEDA

Messier 31, or the Andromeda Galaxy, Earth's largest neighbour, has been devouring smaller galaxies for at least 10 billion years. In another 4.5 billion years, the Andromeda Galaxy and our Milky Way will collide, although it's not yet clear who will devour who in that cosmic pile-up. Unfortunately, earthlings will not be around to see this clash play out, as our Sun is heating up and will likely make life on Earth impossible between about 1 and 5 billion years from now.



Source: wikipedia Commons © Kanwar Singh



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10 DOOMED GALAXY

NGC 3359

With possibly the cutest nickname for a galaxy, the 'Little Cub' sits in the constellation of Ursa Major. This dwarf galaxy has been largely dormant since the Big Bang, meaning it might contain molecules unchanged since just moments after the rapid expansion of the universe 13.8 billion years ago. Little Cub is also doomed. It's being consumed by its larger neighbour, a Milky Way-like galaxy called NGC 3359. Still, the opportunity to watch NGC 3359 strip the star-forming gases from the Little Cub is valuable to science; astronomers may be able to measure the signatures of those early universe molecules before they're gone.

11 ARRESTED DEVELOPMENT

NGC 1277

When you're a galaxy, you've got to consume other galaxies or die. NGC 1277 chose the latter. This galaxy, first reported in 2018, is a mere 240 million light years from Earth. It hasn't formed new stars for about 10 billion years. Astronomers believe that NGC 1277 became stunted because it's moving too fast to gobble up other galaxies in its gravitational pull. It's travelling through space at about 3.2 million kilometres (2 million miles) per hour. Without gas and dust from other galaxies, NGC 1277 no longer forms stars. Some astronomers think that most galaxies started out looking a lot like NGC 1277, evolving spirals and other shapes only through later mergers.



©ESA/Hubble

12 THE TADPOLE

TADPOLE GALAXY

300 million light years away, an enormous tadpole swims through space. This galaxy has a tail that's 500,000 light years long and is ten times longer than the Milky Way. But what created this odd galactic shape? A cosmic collision where two disc galaxies pulled on a smaller dwarf galaxy, clumping the stars on one end into a 'head' and leaving the others to stream out in a long 'tail'. This arrangement is for a limited time only, though. In a few billion years, the galaxies will merge together with some others in the vicinity to create one single galaxy.



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13 MISSING MATTER

NGC 1052-DF2

In 2018, Hubble spied something never seen before: a galaxy with almost no dark matter. Dark matter is a mysterious form of matter that interacts with gravity, but not with light. It makes up more of the total matter in the universe than the matter we can see, so finding a galaxy without any was bizarre, to say the least. A year later, scientific sleuths solved the mystery: NGC 1052-DF2 was not 65 million light years away, as originally believed. It's really only about 42 million light years away. That change in distance completely altered the calculations for the galaxy's mass. Turns out it's a pretty normal galaxy after all, and the universe makes sense again... sort of.



©ESA/Hubble



Source: Wikipedia Commons © Judy Schmidt

"THE LIGHT COMING FROM MESSIER 90 IS SKEWED TOWARDS THE BLUE END OF THE LIGHT SPECTRUM"

14

COMING OUR WAY

MESSIER 90

Most galaxies that scientists observe appear to be moving away from Earth because space is still expanding. But not Messier 90. This spiral galaxy is about 60 million light years away and is moving towards the Milky Way. Astronomers can detect this movement because the light coming from Messier 90 is skewed towards the blue end of the light spectrum. Objects moving away from Earth are redshifted, meaning their light emissions are weighted towards red. Messier 90 is part of a large group of galaxies called the Virgo Cluster. It can be seen from the Northern Hemisphere in May with a telescope or binoculars, sitting between the constellations Virgo and Leo.



BABY PLANETS MARINATE IN A LIFE-GIVING CYANIDE 'SOUP'

New data may have filled gaps in our understanding of planet formation

Reported by Adam Mann

The universe may be teeming with the molecules needed for life. The results come from the most comprehensive maps ever made of the types and locations of chemicals in the gas and dust surrounding newborn stars.

Stars spring from enormous clouds of gas and dust, which collapse under their own weight into disc-like structures. The centres of these discs heat up through friction and increased pressure until they ignite into fusion-powered stars, while the surrounding matter slowly clumps together into ever-larger chunks.

"We have known for some time that planets form in discs around young stars and that these discs contain molecules of interest for predicting the future compositions of planets," said Karin Öberg, an astrochemist at Harvard University in Cambridge, Massachusetts. A few years ago, Öberg and her colleagues decided to use the Atacama Large Millimeter/submillimeter Array (ALMA) – a telescope in Chile that sees in the radio part of the electromagnetic spectrum – as part of the Molecules with ALMA at Planet-forming Scales (MAPS) program. Because of their shapes and the bonds inside them, different chemicals vibrate in unique ways, producing telltale signatures that ALMA can capture.

The team looked at five protoplanetary discs, all between 1 million and 10 million years old, within a few hundred light years of Earth. "That means they are in an actively planet-forming epoch," Öberg said.

MAPS determines not only the specific molecules in protoplanetary discs, but also their locations. "Planets can form at many different distances from the star," Öberg said, so it's important to know what chemicals are available in each location to build these future planets.

An astounding 20 papers from this extensive mapping project are being published in a special future issue of *The Astrophysical Journal Supplement Series*; the first of these papers was made available on the preprint server arXiv on 15 September. "What's so awesome is that there are several pieces rather than one big answer," Öberg said. "I think all 20 papers provide some different piece of the puzzle."

One of the most exciting findings for her was the abundance and distribution of a class of molecules known as cyanides. The simplest member of this family, hydrogen cyanide, is typically considered a poison, though many theories for the origin of life include a major role for this chemical class, she said.

"Seeing them in large abundance means planets are forming in the kind of soup we'd like to see" in order to fuel the emergence of life, Öberg added.



Cyanides also tended to be concentrated towards the inner parts and midplanes of the discs studied by MAPS – exactly where planets are expected to arise, she explained.

Such molecules could form only in a low-oxygen environment with lots of carbon, Öberg added. This suggests that planets will be born with carbon-rich atmospheres – another point in favour of living things, since carbon is the basis of organic chemistry.

The results show at least some of the organic building blocks of life are probably available in other stellar systems, but that doesn't necessarily make it more likely for humanity to find living organisms elsewhere. "It's promising from an origin-of-life point of view," Öberg said. "But there's still a lot of work to do."

Living creatures would have needed a certain subset of chemicals in specific amounts in order to arise spontaneously, and scientists have yet to agree on what that recipe for life was. There has been a lot of past effort into understanding the chemistry in the clouds that give rise to stars, as well as into analysing the molecules in asteroids and comets, which can contain information about later periods of planetary formation, said Kathrin Altwegg, a planetary scientist at the University of Bern in Switzerland, who was not involved in the new work.

"But there was one stage missing," said Altwegg – the stage that determined the chemistry in protoplanetary discs – and the results from this project are now helping to fill in unexplored details. The findings also imply that a great deal of complex chemical formation already takes place prior to the birth of stars and planets, suggesting that these molecules come from interstellar clouds and are widespread in space, she added.

"THE FINDINGS ALSO IMPLY THAT A GREAT DEAL OF COMPLEX CHEMICAL FORMATION ALREADY TAKES PLACE PRIOR TO THE BIRTH OF STARS"

© NASA/JPL-Caltech



© Tobias Roetsch

FINDING AND DEFINING EXOMOONS

As our catalogue of exoplanets grows, the hunt is on for moons around distant worlds

Reported by Robert Lea

Astronomers may have finally discovered a moon orbiting around a planet outside our Solar System. The development could have important implications for our understanding of how planetary systems evolve, as well as indicating how typical the planets of our Solar System are. Since the first discovery of planets around stars other than the Sun was made in the early 1990s, our catalogue of planets outside the Solar System has burgeoned, now containing over 4,000 confirmed worlds. One of the most important aspects of our investigation of these extrasolar planets – or exoplanets – is the assessment of how similar or diverse they are in comparison to the planets of the Solar System.

It's unsurprising given how Earth's own Moon has dominated our imagination and played a vital role in both astronomy and humanity's exploration of space that the hunt for moons around these extrasolar worlds – or exomoons – is a subject of intense interest. This is compounded by the fact that moons are abundant in the Solar System, with an average of 20 moons for each planet. And we have no reason to believe that our planetary system is unique in this respect, making the elusive nature of exomoons confusing and frustrating.

To understand why the discovery of exomoons may be important, it's worth considering just how influential some researchers believe our natural satellite was to the development of life on Earth. This is coupled with the fact that many scientists theorise that if life exists elsewhere in the Solar System, aside from Mars, the most likely places to find it would be on the moons of gas giants Jupiter and Saturn, with the icy moon Enceladus being a particularly enticing suspect. This means that exomoons could be a target for habitability investigations in their own right, especially when they orbit gas giants and could potentially be the size of Earth, or even larger.

Determining if an exoplanet is orbited by a moon could be important for investigations of that planet's habitability potential in another way. For rocky terrestrial exoplanets in the habitable zones of their stars – the area that has the right temperature to allow for the existence of liquid water – an undetected moon may add an additional source of thermal or reflected light that hinders the determination of characteristics belonging to the planet itself.

Observations of our Solar System, in which moons are plentiful, suggest that such objects should be extremely common throughout other systems. However, until recently these exomoons have proven to be particularly elusive. This could be because our detection methods are not sensitive enough as of yet to spot these moons outside the Solar System, or because moons are less common in other planetary systems for some reason. Determining which of these possibilities is correct is an important and missing aspect of our ongoing investigations of extrasolar planetary systems.



© Alamy

Left: Zodiacal light over La Silla Observatory in Chile

Below: If alien worlds are anything like those in our Solar System, moons should be plentiful

TYPES OF EXOMOON

How we can categorise the alien moons we expect to find

SNOWBALL EXOMOON

A snowball exomoon is one where the entire moon is permanently frozen, and less than one-tenth is habitable. These worlds are likely to have been born far from their stars, or were perhaps moved there from a position nearer the star.



HABITABLE EXOMOON

Habitable exomoons are defined as those where at least a tenth of the surface could support liquid water. These will need to be in the star's habitable zone, as well as the right distance from the planet, but could be great bets for finding life elsewhere.



TRANSIENT EXOMOON

A transient exomoon is said to be sort of habitable, but its habitability changes dramatically over time. The idea that a moon may shift in and out of habitability will need careful consideration when we look for and study exomoons.



HOT EXOMOON

Researchers Duncan Forgan and Vergil Yotov came up with a system for classifying exomoons in 2014. One class was a hot exomoon, defined as one with an average surface temperature of more than 100 degrees Celsius (210 degrees Fahrenheit), with less than one-tenth being habitable.



Discovering exoplanets, though not easy, relies on several tried-and-tested methods. The most powerful of these is the transit technique – used by both Kepler and NASA's Transiting Exoplanet Survey Satellite (TESS) – which hinges on observing the tiny dips in light from a distant star as an orbiting planet crosses its face. The transit technique used to detect exoplanets is also being used to hunt for exomoons, though undeniably with less success. To understand why the transit technique – the most successful exoplanet-hunting method, yielding thousand of discoveries – may not be as successful in detecting exomoons, consider what astronomers must spot to indicate the presence of a lunar body.

Like cosmic nesting dolls, to spot an exomoon using the transit method, astronomers would need to observe a transit within a transit – a situation in which as a planet transits its star, its moon is also visible transiting the star's face. Even if this occurred and we were lucky enough to catch it, the observation would have to be made with equipment sensitive enough to spot the exomoon and distinguish the dip in light it causes from the dip in light caused by its parent planet.

Furthermore, even large exoplanets cause just tiny dips in the light signature of their parent stars, so imagine how small a reduction in light would be when caused by an exomoon, being much more diminutive than its host planet. Another issue with detecting exomoons is related to the kinds of exoplanets that the highly successful transit method is best at spotting, as these may not be planets that are best suited to hosting moons. The transit method excels at discovering large planets that are very close to their parent stars. This is based on the simple logic that the larger a planet is, and the closer it exists to its star, the more light it will block when it crosses that star's face. This creates a more prominent signal for astronomers to identify and distinguish from background noise.



© Getty

Extremely proximate planets are often tidally locked to their stars – as is the case with Mercury – and thus their rotation slows. This proximity can mean that one face of the planet permanently faces its star, becoming blisteringly hot, resulting in a world with a permanent dayside and nightside. But it has another effect, and it's one that has a significant impact on the chance of an exoplanet holding onto natural satellites. When orbiting around a planet, a moon or any other natural satellite will often have a synchronous orbit. For an orbit to be stable, this needs to be within what is called the Hill sphere – the hypothetical region around a planet in which it dominates the gravitational attraction of objects. For exomoons, this is a limiting radius at which they may be gravitationally bound and remain stable.

As the rotation of a planet is slowed, the synchronous orbit is pushed out, away from that world. For tidally locked exoplanets that barely spin – if at all – this orbit is pushed beyond the Hill sphere. This means that any potential moons within the Hill sphere will not have a stable synchronous orbit and will thus spiral towards the planet. Meanwhile, moons outside the Hill sphere will likely escape the planet due to the lack of gravitational influence they experience, thus never reaching the synchronous orbit.

There is another hindrance to exomoon possession experienced by exoplanets that exist close to their parent stars. Many of these

HUNTING FOR EXOMOONS

Kepler helped us find many exoplanets that may host natural alien satellites

1 SUNSHADE

As the name suggests, the sunshade blocked the Sun's rays from the photometer so it could observe the universe without being blinded or obstructed.

2 PHOTOMETER

The most important instrument on Kepler was the photometer, which looked at stars to notice dips in their light as planets pass in front, known as a transit.

3 REACTION WHEELS

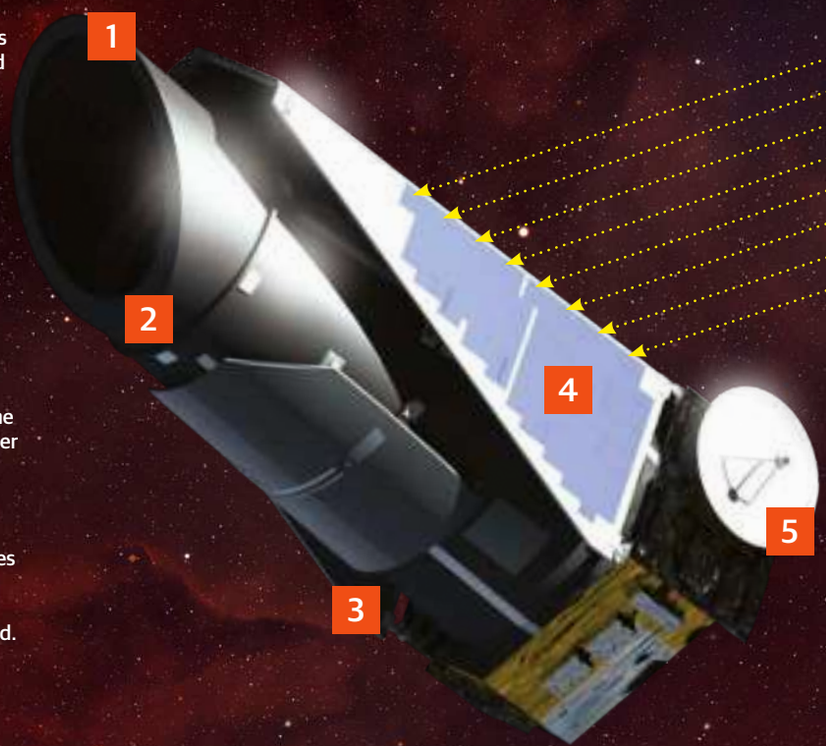
These were used to point the telescope at distant stars in order to find planets.

4 SOLAR ARRAY

Kepler had to roll 90 degrees every three months to keep its solar panels pointed at the Sun and keep the telescope powered.

5 HIGH-GAIN ANTENNA

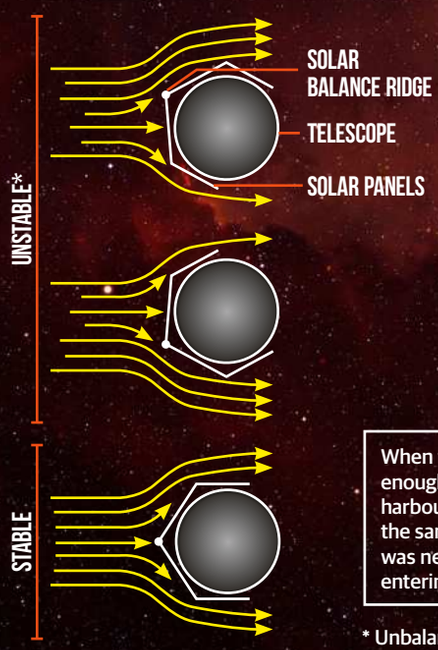
This was used to communicate with Earth, receive commands and send back data on any exoplanets Kepler found.

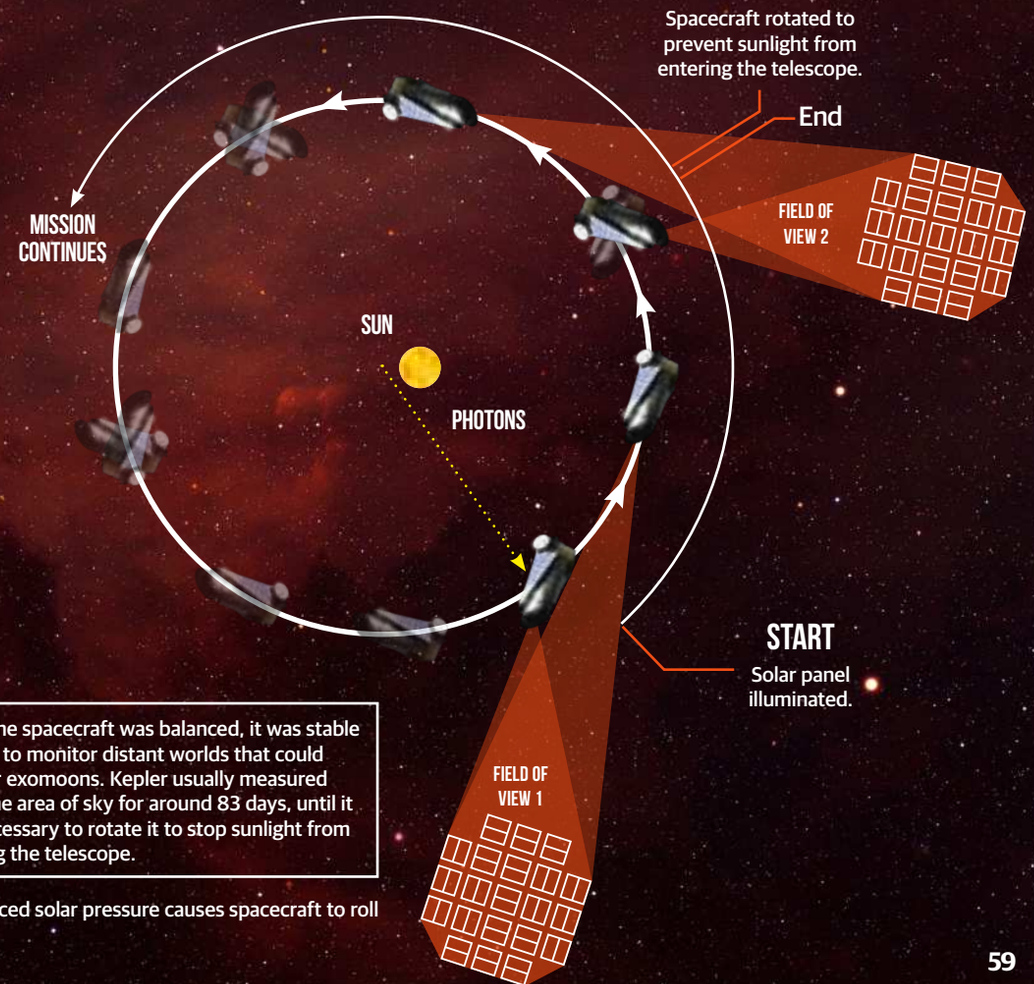


SOLAR BALANCE RIDGE

Photons in light emitted by the Sun exerted pressure on the Kepler space telescope, allowing the spacecraft to be properly balanced against the pressure.

TOP-DOWN VIEWS OF THE SPACECRAFT





When the spacecraft was balanced, it was stable enough to monitor distant worlds that could harbour exomoons. Kepler usually measured the same area of sky for around 83 days, until it was necessary to rotate it to stop sunlight from entering the telescope.

* Unbalanced solar pressure causes spacecraft to roll

exoplanets orbit their stars with a period of a few days, while others take just hours to circle their parent star. In simulations published in May 2021, researchers from the University of Groningen used a simplified model of one exoplanet, orbiting a single star and possessing a single exomoon, to determine how likely such a world would be to hold its moon as different parameters were altered.

Watching the model evolve over a period of 10 billion years, the team tested how changing the masses of the components of the system changed the prospects of the planet holding onto its moon. They also adjusted the distance at which the exoplanet orbits its star. This highly simplified model suggested that the orbital period of the exoplanet was key to retaining an exomoon. For exoplanets with orbits ranging from 300 days – similar to the orbit of Earth around the Sun – to ten days, the survival rate of exomoons dropped from 70 down to 0 per cent. The team's model suggests that for planets so close to their host stars that they complete an orbit in less than ten days, there was no stable orbit for a moon.

These results reflect observations of our own planetary system, with the two innermost planets – Mercury and Venus – lacking moons and Earth possessing its own large natural satellite. Jupiter and Saturn, both larger planets that are more distant from the Sun, host large collections of moons. Because the majority of the planets in our current exoplanet catalogue were discovered using the transit method, and this method favours planets close to their parent stars, all this means is that there's a bias in the exoplanet catalogue that disfavours planets with exomoons. Yet despite the difficulty associated with detecting exomoons, several possible exomoon identifications have been made. But these potential exomoon detections are still controversial.

In January 2022, a new paper published in the journal *Nature Astronomy* revealed that astronomers had discovered a signal that indicates the presence of a moon outside the Solar System. The discovery was made during an investigation of observational data of 70 suspected massive and cool exoplanets that cross – or transit – the face of their parent stars. These exoplanet candidates had been discovered by the Kepler space telescope, which launched in 2009 and was retired in 2018. In this survey, the research team discovered just one signal that could indicate the presence of an exomoon, which has been named Kepler 1708b-i.

The potential exomoon has a proposed radius around 2.6 times that of Earth's. It orbits a world about the size of Jupiter that takes approximately 400 days to complete an orbit of its star. Whether scientists come to consider Kepler 1708b-i to be the first detected exomoon hinges on further investigation of a signal determined by the same group of astronomers in 2018. It's an observation that has been the subject of intense debate in scientific circles.

In a separate paper published in *The Astrophysical Journal*, a team of astronomers revealed a signal that could indicate the presence of an exomoon around the exoplanet Kepler-1625b, a Jupiter-sized gas giant orbiting a yellow star over 8,000 light years away from Earth. The team spotted the telltale dip in light caused as an object

HOW TO FIND AN ALIEN MOON

The different methods being used to hunt for exomoons

TRANSIT TIMING METHOD

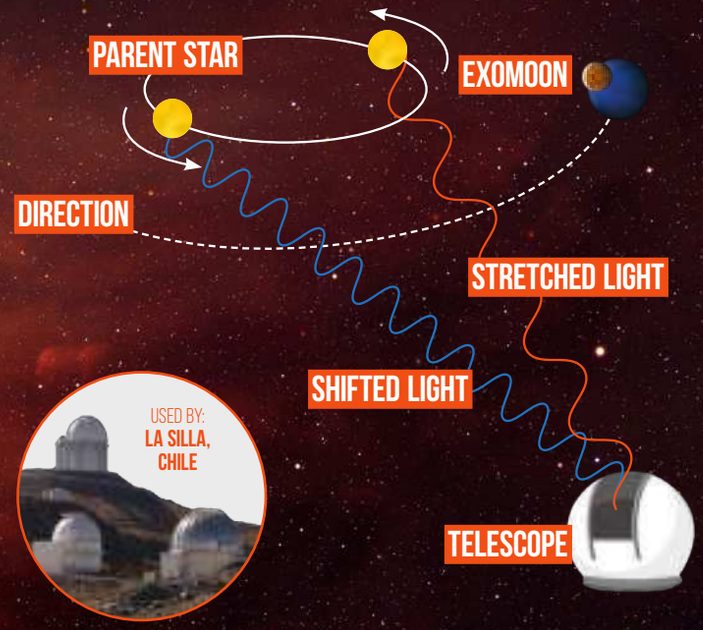
The transit timing method works by measuring a change in the regular transit of a planet. As a planet swings around a star, if there are other objects in its vicinity then it can affect how often a transit is completed. This often indicates the presence of other planets in the system, but in theory the method could be used to hunt for large exomoons as well, revealing their tug on their parent planets. It's hard to distinguish between an exoplanet and an exomoon via this method, though, so it might be difficult to make a discovery with it.



© NASA

RADIAL VELOCITY METHOD

When an exoplanet orbits a star, its gravity can cause a tug on the star, making its presence noticeable to us on Earth. The star's spectrum of light is shifted to the blue end of the spectrum if the planet's coming towards us, and the red end if it's going away. Using this method, some characteristics of the planet can be determined. Like the transit timing method, it's thought that the same principle could be applied to exomoons, noticing their effect on a planet. Again, though, the effect is so small that it would be hard to find exomoons using this method.



crosses the face of a star, suggesting that it was possibly caused by an exomoon, which was given the designation Kepler-1625b I. The observations made by the team – collected with both the Kepler and Hubble space telescopes – were reassessed the following year by two separate teams of researchers. Both teams were sceptical that an exomoon had been detected around Kepler-1625b, albeit to varying degrees.

In a paper published to **arxiv.org** on 25 April 2019, one set of researchers, including Harvard-Smithsonian Center for Astrophysics astronomer Laura Kreidberg, failed to see a moonlike dip in the initial data. They concluded that the light curve of the star Kepler-1625 best conformed to a star transited by a planet alone. A second independent team of scientists, including Max Planck Institute for Solar System Research astronomer René Heller, was only slightly more optimistic. They analysed the same data, finding that signs of Kepler-1625b I were inconsistent.

In a paper published in *Astronomy & Astrophysics*, Heller and his colleagues point to

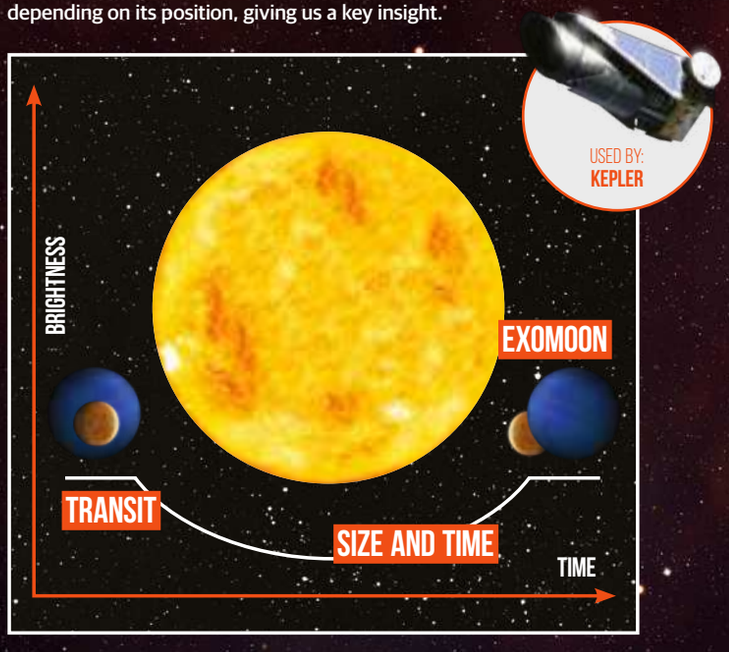
Right: With so many stars in our galaxy alone, there surely must be an exomoon out there



Source: Wikipedia Commons © ScottRak

TRANSIT METHOD

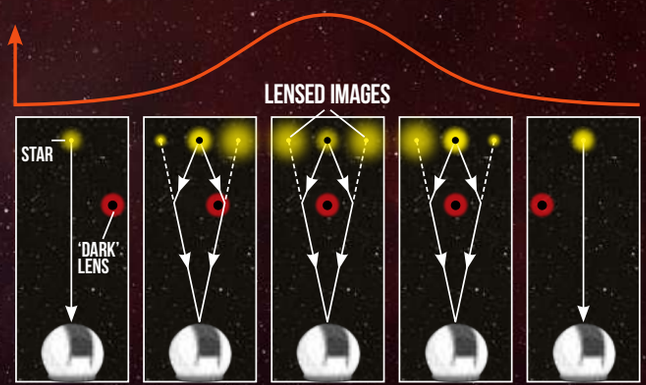
Many exoplanets have been found using the transit method. As a planet periodically orbits its star, it causes a dip in the star's light – or flux – if it crosses our line of sight. Measuring this dip, we can then determine the orbital period and even the size of the planet. The same method could also be used for exomoons, noticing the combined dip produced by both the moon and its planet. Indeed, as the moon will be moving around the planet, it may block a different amount of light depending on its position, giving us a key insight.



MICROLENSING



Gravitational microlensing is essentially the result of an object in the universe magnifying a much more distant object. For example, an intermediate star can boost the light of a more distant galaxy, although any given event will occur only once. If the intermediate star has a planet orbiting it, then the effect is altered, and the presence of the planet can be deduced. More recently, it has been suggested that this same method could be used to detect exomoons.



LIGHT

The light from a distant star travels and is picked up by telescopes.

LENSING

The star's light is bent around a massive foreground object.

DOUBLED

The effect causes us to see multiple versions of the distant star.

RING

The effect can cause a ring of light known as an Einstein ring.

UNIQUE

These events only happen once, so there's no opportunity for a repeat.

unknown systematic errors in the Kepler and Hubble data making the finding unreliable, writing that: "Although we find a similar solution to the planet-moon model to that previously proposed, careful consideration of its statistical evidence leads us to believe that this is not a secure exomoon detection."

With more and more exoplanets being discovered, a picture has developed of a universe that is far more varied in terms of worlds than we previously believed. Astronomers have discovered examples of planets for which there are no analogues in our increasingly mundane Solar System. This includes exoplanets like hot Jupiters, those larger than the Solar System's most massive planet which exist so close to their stars they whip around in days or even hours, and rogue planets that wander the galaxy alone, separated from their parent stars. There's a chance that as we discover more exomoons this diversity will be continued through to these smaller bodies, further revealing that the universe can be a strange place.

One exomoon candidate suggested recently is an example of this, and it could provide a solution to a long-standing astronomical mystery. For some time now astronomers have observed the dimming of a distant star called KIC 8462852, or Tabby's Star as it's more commonly known. Many possible mechanisms have been suggested for this often abrupt dimming, ranging from the relatively mundane, like obscuration by dust, to the more 'out there' like black holes, obscuring comets and even to the seemingly fanciful notion of alien 'megastructures'.

In a 2019 paper published in the *Monthly Notices of the Royal Astronomical Society*, it was suggested that the dimming could be the result of a melting exomoon. The authors of the study, including University of Columbia astrophysicist Brian Metzger, posit that this exomoon, composed mainly of ice and rock, is evaporating, and in the process is spewing off material that obscures the light from the star. Not only would this explain the gradual dimming of Tabby's Star that saw it drop in brightness by about 14 per cent between 1890 and 1989, it could also explain random or sporadic fluctuations in the star's brightness of between 1 and 22 per cent. The team also considered that this exomoon may have been detached from its exoplanet host by powerful tidal interactions with the parent star. This interaction, which could have seen the exoplanet destroyed, may have placed the moon in orbit around Tabby's Star, where it began to slowly disintegrate.

Another extreme exomoon candidate spotted in 2019 could be volcanically active like Jupiter's moon Io. Located in the exoplanet system of WASP-49b, astronomers discovered a signal that could indicate a dangerous volcanic moon with a molten surface of lava – almost a lunar version of



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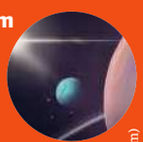
Above: Illustration of a rocky world with two exomoons in orbit

Right: The Keck Observatory in Hawaii is involved in the hunt for exoplanets – and by extension their moons

EXOMOON CANDIDATES

There are a few examples that need further study for confirmation

KEPLER 1708B-I



© Helena Valenzuela Widerström)

Distance from Earth: 5,436 light years

Host planet: Jupiter-sized planet Kepler 1708b

Host star: F-type star Kepler 1708

Exomoon size: Mini-Neptune

Discovered: 2022

KEPLER-1625B I



© NASA/ESA

Distance from Earth: 8,154 light years

Host planet: Jupiter-sized gas giant Kepler-1625b

Host star: Kepler-1625 has a similar mass to the Sun but is 70 per cent larger

Discovered: 2018

Size: Neptune-sized

WASP-49B'S 'EXO-IO'



© University of Bern, Illustration: Thibaut Roger

Distance from Earth: 635 light years

Host planet: WASP-49b a gas giant with a mass 0.37 times that of Jupiter and a similar radius

Host star: WASP-49, a yellow dwarf main-sequence star

Size: Unknown

Discovered: 2022



WHY OUR MOON IS IMPORTANT



From protecting us from asteroids to creating tides on Earth

IT LIGHTS UP THE NIGHT SKY

It's not always bright, but when it is the Moon can provide an excellent source of light at night, useful not only for humans but for animals as well.

IT KEEPS US SAFE FROM ASTEROIDS

The Moon plays a role in keeping us safe from impacts, either deflecting asteroids or taking hits, although the extent of this is debated.

IT CREATES TIDES ON EARTH

Without the Moon, we wouldn't have lunar tides, one of the drivers for spreading nutrients through the ocean, and life would struggle to survive.

IT KEEPS OUR PLANET STABLE

One of the Moon's most important facets is that it stops our planet wobbling too much on its axis, keeping us stable as we orbit the Sun.

IT SLOWS DOWN OUR PLANET

Without the Moon, our planet would rotate a couple of seconds faster every 100,000 years. Over Earth's history, this would amount to a day shorter by several hours.



© Alamy

the super-Earths that orbit their stars at extremely close proximities. The team behind the discovery, who originate from the University of Bern, suspect that the exomoon orbits a hot Jupiter that orbits its star with a period of just three days. Evidence of the exomoon was provided by observations of sodium gas around WASP-49b, located 635 light years from Earth, at an anomalously high altitude. The astronomers also discovered a further four systems that could host similar evaporating exomoons. As is the case with the other exomoon candidates, the confirmation of these exomoons may well rely on further investigations of the planetary systems in question.

Set to be instrumental in this is the James Webb Space Telescope (JWST), launched on 25 December 2021. With future projects like the JWST opening up opportunities to discover exomoons in distant planetary systems, one possible outcome of a deeper study of exomoons may be the revision of what we think of as a moon.

As exomoon discoveries continue, the definition of what we call a moon could become blurred in a similar way to how brown dwarfs have caused us to question the boundary between planets and stars. Often described as failed stars due to the fact they lack the mass to trigger the nuclear fission processes that define stars, brown dwarfs could possess bodies that orbit them. But if brown dwarfs are classed as planets rather than stars, shouldn't we then define the bodies in orbit around them as moons? That was a major question raised by a team of researchers who in 2019 collected data that suggested two tremendously massive exomoons are orbiting two distant brown dwarfs.

One of these brown dwarfs has around 10 or 11 times the mass of Jupiter and seems to be orbited by an exomoon around the same mass as the king of the Solar System, while the other brown dwarf has a mass around 13 to 14 times that of Jupiter with an exomoon that's almost five times the gas giant's mass. The planetary system discovered by the team, including University of Padova researcher Cecilia Lazzoni, who presented the results at the fourth Extreme Solar Systems conference in Reykjavik, Iceland, in 2019, is like nothing researchers have ever discovered before. If these potential exomoons can be confirmed, their immense mass means researchers will have to decide if they fit the definition of a moon at all.



Robert Lea
Space science writer
Rob is a science writer with a degree in physics and astronomy. He specialises in physics, astronomy, astrophysics and quantum physics.

Focus on

ROGUE BLACK HOLES COULD BE WANDERING AT THE EDGES OF THE MILKY WAY

New simulations show these behemoths might dwell far from galactic centres

Reported by Ben Turner

An enormous number of rogue supermassive black holes may be wandering around the universe. In fact, wandering giant black holes may account for a whopping ten per cent of the nearby universe's black hole mass 'budget'. This means that galaxies like our own could have an average of 12 invisible behemoths prowling around their outskirts, gobbling up anything that gets in their way. Because the number of black holes increases the more mass there is in the outer 'halo' of material that surrounds galaxies, clusters of galaxies, which have heavy halos, could have even more of the ravenous wanderers.

Just as a basket can be woven around the supporting structure of a stone, astronomers think that most galaxies form around supermassive black holes. These gigantic gravitational beasts, often many millions or even billions of times more massive than the Sun, act as anchors for long trains of gas, dust, stars and planets that swirl in orbit around them. Closer to the black holes, this material spirals faster and heats up, forming an accretion disc that both feeds the black hole and produces the telltale radiation that makes it visible.

Usually the mass of the black holes cements them in the centres of their galaxies, which slowly orbit around each other in clusters called galactic groups. But sometimes an enormous force – such as a collision between two galaxies – can pop a central supermassive black hole loose, forcing it to wander the universe like a hungry cosmic vagabond.

These wandering monsters can also be set loose when the merging of two black holes is disrupted, sending them both flying. To estimate how often this occurs, astronomers ran a set of simulations called Romulus, which accounts for all known rules about how black holes behave to trace how their orbits might evolve over billions of years.

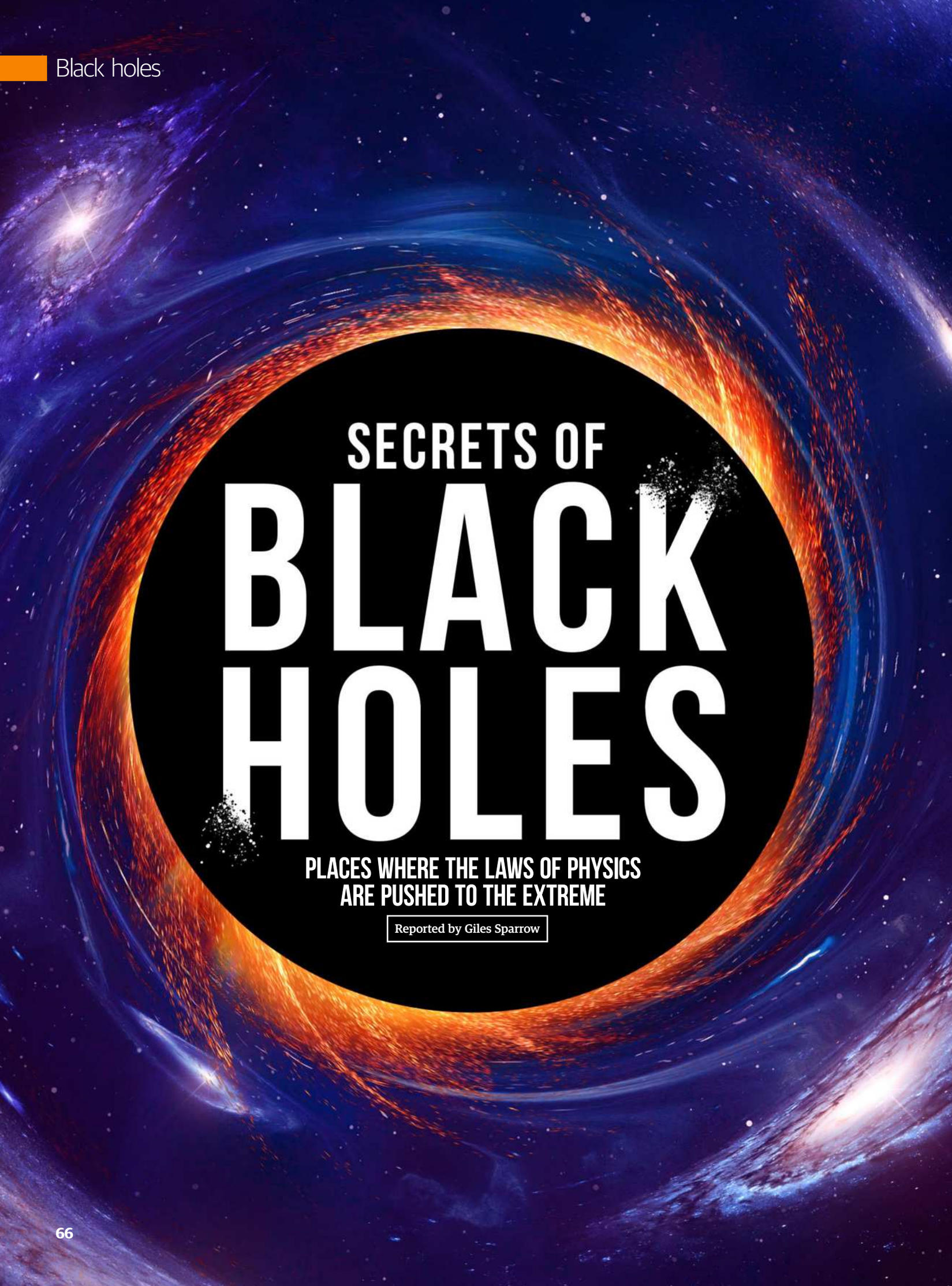
The simulations predicted that the frequent galactic collisions of the early universe, between the time of the Big Bang about 13.8 billion years ago and roughly 2 billion years later, produced enough wanderers to outnumber – and even outshine – their galactically fixed supermassive black hole cousins. Later, as the universe grew older, many of the loose black holes merged and were recaptured by other supermassive black holes after forming binary systems with them in the centres of galaxies, the simulations found. But many also remained free.

According to the astronomers running the Romulus simulation study, "Romulus predicts that many supermassive black hole binaries form after several billions of years of orbital evolution, while some SMBHs [supermassive black holes] will never make it to the centre.

"As a result, Milky Way-mass galaxies in Romulus are found to host an average of 12 supermassive black holes, which typically wander the halo far from the galactic centre." The researchers' next steps will be to figure out possible hallmarks of the lost invisible giants' presence in the universe so that one day soon we can observe them firsthand.

Below: The Milky Way could have up to 12 SMBHs lurking at its fringes

©Getty



SECRETS OF BLACK HOLES

PLACES WHERE THE LAWS OF PHYSICS ARE PUSHED TO THE EXTREME

Reported by Giles Sparrow

Black holes are the most mysterious objects in the universe. They're places where physics is pushed to its most extreme, where light cannot escape and where space-time itself is twisted and even punctured, leading to the most incredible and counter-intuitive phenomena. A black hole is a region of space where gravity is so strong that nothing, not even light, can escape from its grasp. Within a certain proximity of one, closer than the black hole's 'event horizon', you'd have to travel faster than light to get away from it. Since nothing can go faster than light – at least as far as scientists know – then whatever falls down a black hole stays down the black hole.

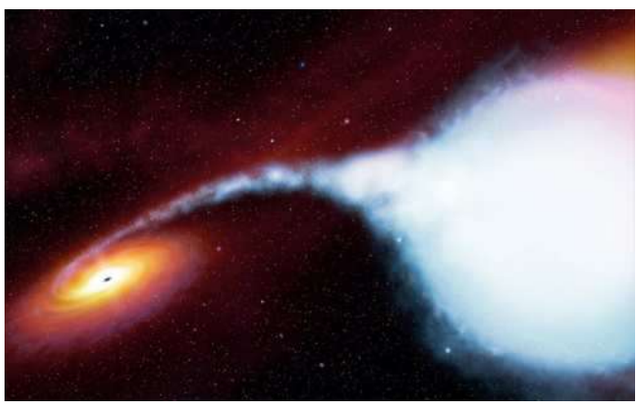
The discovery of black holes dates back to Einstein's general theory of relativity. Einstein himself didn't predict the existence of black holes per se, but general relativity, which describes mass, space, time and gravity, provides the mathematical foundations for understanding them. These were realised by Einstein's German compatriot Karl Schwarzschild, who solved Einstein's equations to describe the gravitational field around a non-rotating, spherical mass and to determine the Schwarzschild radius, which is the size of a black hole's event horizon. In the 1960s, Roy Kerr solved Einstein's equations for a more realistic scenario – that of a black hole that's spinning.

We've already mentioned that light cannot escape a black hole, and the event horizon is its ultimate boundary of no return. Once something has crossed the event horizon's invisible boundary, it can never return from the black hole. Let's picture what is going on using an oft-mentioned analogy, that of a rubber sheet, which we have to imagine as being the fabric of space for this analogy to work. If you want to try this at home, a bedsheet held tight at each corner should suffice. Place a marble onto the sheet. In our example, that's Earth. Notice how it causes the sheet to dip a little. In general relativity, that dip in the fabric of space is called a gravitational well – it represents Earth's gravitational field. Now put a tennis ball on the sheet, imagining that it's the Sun. You'll notice that it creates a bigger dip than the 'Earth', not necessarily because it's larger, but because it has more mass. If you were to zip ball bearings past both the marble and the tennis ball, they'd need more energy to get past the tennis ball without falling into its steeper gravitational well.

Now, put a cannonball on the rubber sheet – if you're trying this at home you probably don't have a cannonball to hand, but see if you can use something suitably heavy. It will create a dip so steep that once any ball bearings you roll in its direction get too close to it, they'll always fall into the dip and cannot get out no matter how fast they are moving. Around a real black hole, the event

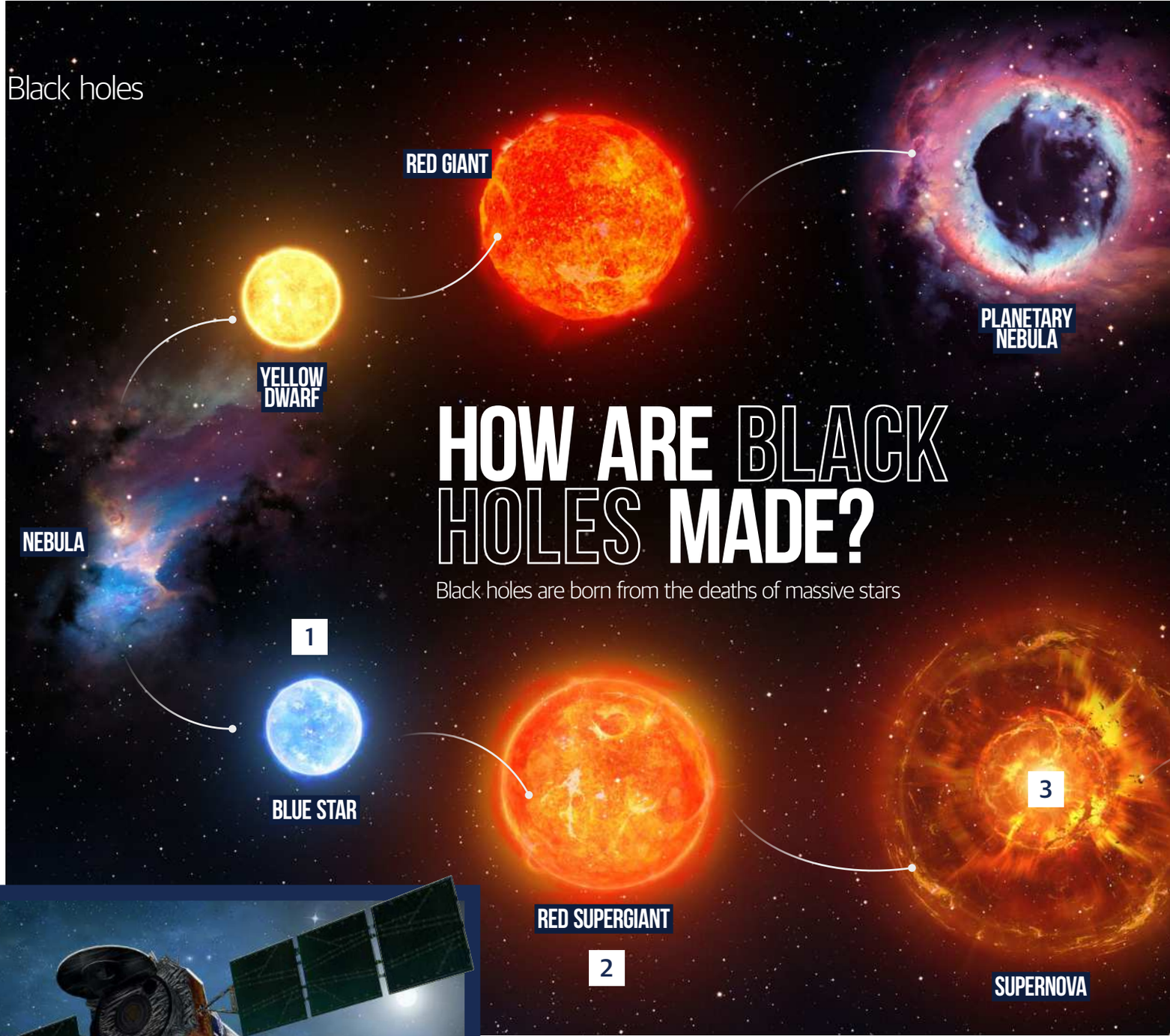
THEY'RE A MASSIVE X-RAY SOURCE

The first observational evidence for a black hole emerged in 1971, coming from a binary star system within our own galaxy. Called Cygnus X-1, the system produces some of the universe's brightest X-rays. These don't emanate from the black hole itself, or from its visible companion star, which is enormous at 33 times the mass of our own Sun. Instead matter is constantly being stripped from the giant star and dragged into an accretion disc around the black hole, and it's from this accretion disc that the X-rays are emitted. As was the case with HR 6819, astronomers used observed star motion to estimate the mass of the unseen object in Cygnus X-1. The latest calculations put the dark object at 21 solar masses, concentrated into such a small space that it couldn't be anything other than a black hole.



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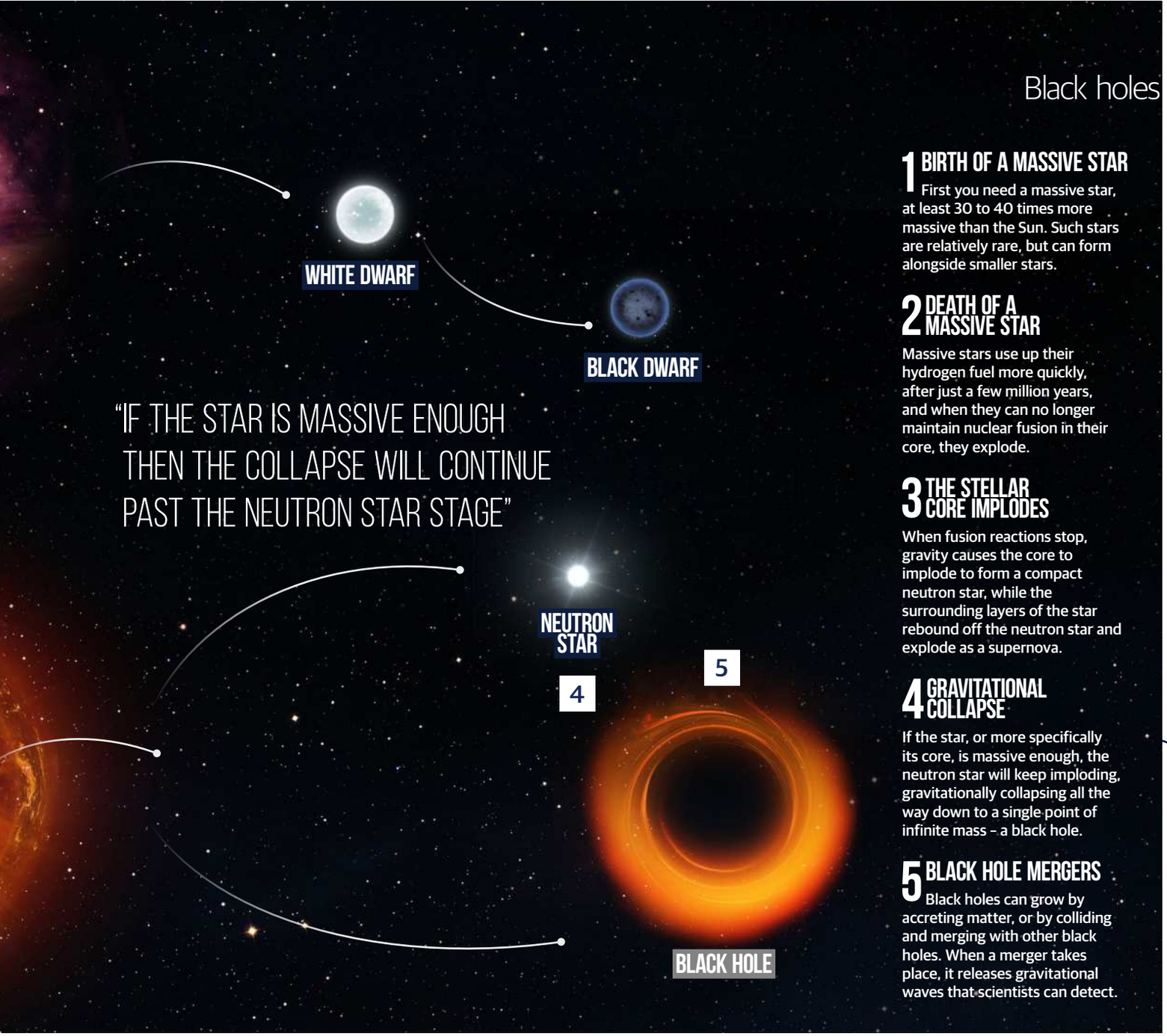
© NASA

Above: Advanced space telescopes might be able to image black holes – or at least their surrounding material

horizon is the distance from the black hole where the dip is so steep that not even light can move fast enough to escape. And that's why black holes are black.

There's so much more to tell about the story of black holes. How are they formed? Where do the things that fall into them go? What exists at the centre of a black hole? And what do black holes do in the centres of galaxies? Let's continue with the easier bit – how they are formed. When our Sun, a star, reaches the end of its life in about 5 billion years, it will expand to become a red giant before gracefully puffing off its outer layers to form a planetary nebula, leaving behind its small, hot core, called a white dwarf. Stars more than eight times the mass of the Sun, however, bow out more explosively. Their huge masses ultimately cause their cores to collapse due to the internal pull of their own gravity, while the rest of the star goes supernova. As the outer parts of the star explode, the collapsing core condenses to become a neutron star, which is so tightly packed that it contains as much, or more, mass as the Sun but is only 20 kilometres (12.4 miles) or so across. If the star is massive enough – at least 30 to 40 times the mass of the Sun – then the collapse will continue past the neutron star stage, imploding and collapsing down to a point of infinite density, the 'singularity' at the heart of a black hole.

In mathematics, singularities are calculations that tend to infinity, usually because of some error, some gap in our knowledge needed to fully complete the equation. This also describes the black hole singularity, in the sense that we don't know the necessary physics to figure the singularity out. That's because at the microscopic scale of the black hole singularity, we enter the world of quantum physics, and scientists don't yet have a theory of quantum gravity. Until we



1 BIRTH OF A MASSIVE STAR

First you need a massive star, at least 30 to 40 times more massive than the Sun. Such stars are relatively rare, but can form alongside smaller stars.

2 DEATH OF A MASSIVE STAR

Massive stars use up their hydrogen fuel more quickly, after just a few million years, and when they can no longer maintain nuclear fusion in their core, they explode.

3 THE STELLAR CORE IMPLODES

When fusion reactions stop, gravity causes the core to implode to form a compact neutron star, while the surrounding layers of the star rebound off the neutron star and explode as a supernova.

4 GRAVITATIONAL COLLAPSE

If the star, or more specifically its core, is massive enough, the neutron star will keep imploding, gravitationally collapsing all the way down to a single point of infinite mass – a black hole.

5 BLACK HOLE MERGERS

Black holes can grow by accreting matter, or by colliding and merging with other black holes. When a merger takes place, it releases gravitational waves that scientists can detect.

do, scientists won't have the tools to be able to mathematically describe a black hole singularity.

Not that any of this prevents astronomers from learning more about what occurs outside the event horizon, where light still escapes. Some black holes can grow to be millions, or even billions of times more massive than our Sun – in case you're wondering, our Sun has a mass of 1.9×10^{30} kilograms, or 1.9 million trillion trillion kilograms. Astronomers aren't entirely sure how black holes grow to be 'supermassive' like this – it's a possibility that supermassive black holes are the result of lots of mergers of smaller black holes created by supernovae, or maybe they are formed by giant clouds of gas that existed when the universe was very young which underwent a dramatic gravitational collapse and imploded to form a massive black hole. However they form,

HOW BLACK HOLES GROW

The earliest black holes to form will be much bigger today



GIANT STAR

The first generation of very massive stars, hundreds of times as massive as the Sun, would have burnt through their nuclear fuel very quickly.



SEED BLACK HOLE

These stars collapsed down to black holes of tens of solar masses, which then acted as seeds for the creation of much larger black holes.



x3 Images © Getty

ACCRETION

Over billions of years, gas and dust spiralling into these black holes increased their mass; this isn't enough to explain supermassive black holes.

ANATOMY OF A BLACK HOLE

1 SINGULARITY
The core of a black hole is a mysterious point of infinite mass called a singularity, where our currently known laws of physics break down.

2 EVENT HORIZON
The point of no return; this is where the gravity from the extreme curvature of space-time is so strong that not even light can escape.

3 ERGOSPHERE
An oblate zone around a rotating black hole, the ergosphere is a volume of space from where energy and mass can be extracted from the black hole.

4 STATIC LIMIT
The edge of the ergosphere. Everything inside the static limit is caught up by the mass of the black hole dragging the fabric of space-time with it as it rotates.

AR SCAN HERE



THEY CAN EMIT GRAVITATIONAL WAVES

Black holes don't always exist in isolation; sometimes they occur in pairs, orbiting around each other. When they do, the gravitational interaction between them creates ripples in space-time, which propagate outwards as gravitational waves. With observatories like the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo, we now have the ability to detect these waves. The first discovery, involving the merger of two black holes, was announced back in 2016, and many more have been made since then. As detector sensitivity improves, other wave-generating events besides black hole mergers are being discovered, such as a crash between a black hole and a neutron star which took place way beyond our galaxy at a distance of 650 million to 1.5 billion light years from Earth.

© Tobias Roetsch

supermassive black holes can be found at the centres of most giant galaxies. For example, our Milky Way has a supermassive black hole at its heart called Sagittarius A*, and it has a mass 4.1 million times greater than the Sun's mass.

The huge gravitational well of supermassive black holes means that they can pull in a lot of surrounding material – gas and dust clouds, asteroids, comets and sometimes even whole stars. This material gets ripped apart by the gravitational tidal forces being wielded by the black hole and can lead to a phenomenon known as 'spaghettification'.

Imagine an unfortunate astronaut floating too close to a black hole. The tidal forces are so great that the gravity pulling on the astronaut's feet will be far stronger than the gravity pulling on their head. This would have the effect of stretching them out to the point that they would be pulled into strings of their respective atoms and molecules. Fortunately, no astronaut has ever fallen into a black hole, but plenty of gas clouds have, and they get spaghettified too.

We can see the consequences of these gas clouds being torn apart around active black holes – the material ripped from the gas clouds forms a disc of incredibly hot gas that encircles the black hole outside the event horizon. Astronomers call such discs 'accretion discs' because the gas is said to be accreting onto the black hole. Friction between the atoms and molecules in the disc, which can be moving around the black hole at high speeds, causes the gas to heat up above a million degrees Celsius (1.8 million degrees Fahrenheit) and shine brightly. So while a black hole itself is dark, the environment just outside an active black hole's event horizon can be highly luminous. Furthermore, the disc is rife with powerful magnetic fields emanating from the black hole, and these can funnel charged particles in the disc towards the black hole's

5 ACCRETION DISC
An active black hole siphons and steals matter, mostly in the form of interstellar gas, from the environment around it. This matter falls towards the black hole in a spiralling accretion disc.

6 RELATIVISTIC JET
Powerful magnetic fields weaving through the accretion disc can funnel charged particles away in beams or jets that emanate from above and below the rotational axis.

4

"FORTUNATELY, NO ASTRONAUT HAS EVER FALLEN INTO A BLACK HOLE, BUT PLENTY OF GAS CLOUDS HAVE, AND THEY GET SPAGHETTIFIED TOO"

WHEN BLACK HOLES COLLIDE

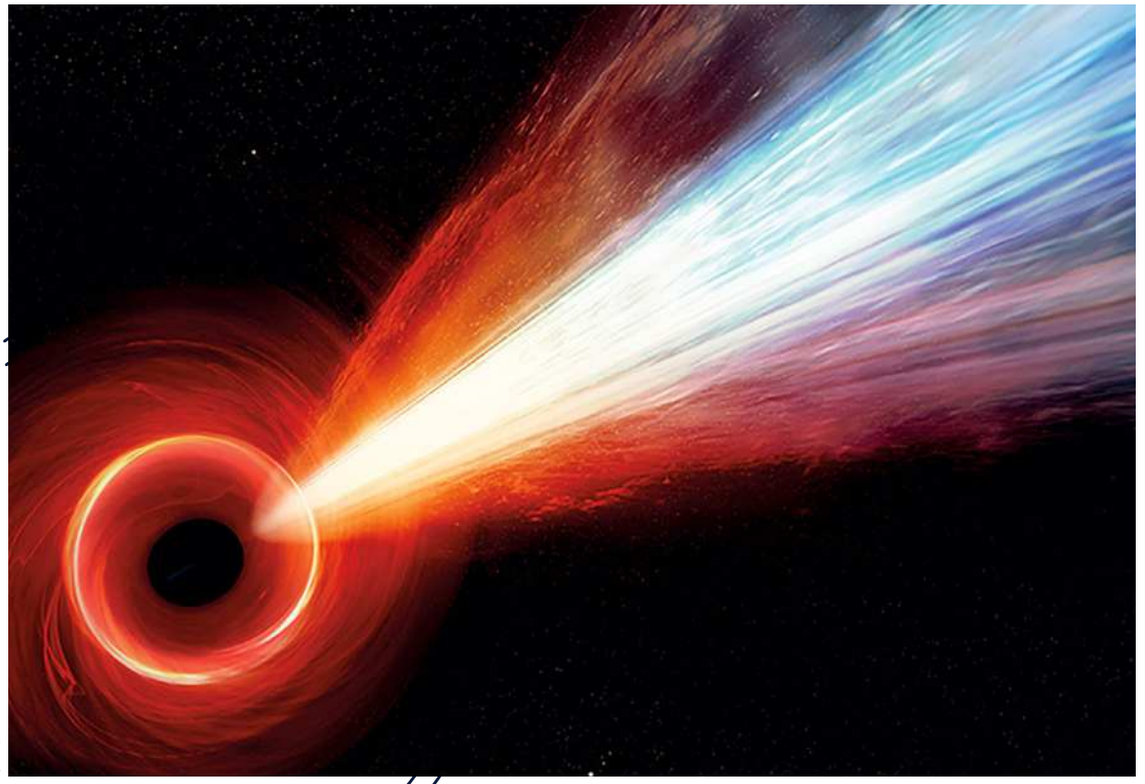


MERGING GALAXIES
Two galaxies crash into each other, initially producing a confused mess of material but then settling down to become a single, merged galaxy.

TWO BLACK HOLES
The black holes that started at the centres of the original galaxies gradually spiral towards each other, eventually coalescing.

HIGH-ENERGY JET
The combined black hole may cause the core of the merged galaxy to eject streams of hot gas and high-speed particles.

VISIBLE CONSEQUENCES
The newly merged black hole gives its presence away through the release of gravitational waves and high-energy radiation.



©NASA

GAMMA-RAY BURSTS ARE EVIDENCE

In the 1930s, Subrahmanyan Chandrasekhar looked at what happens to a star when it has used up all its nuclear fuel. The end result depends on the star's mass. If the star is really big then its dense core – which may itself be three or more times the mass of the Sun – collapses all the way down to a black hole. The final core collapse happens quickly, in a matter of seconds, and it releases a tremendous amount of energy in the form of a gamma-ray burst. This burst can radiate as much energy into space as an ordinary star emits in its entire lifetime. Telescopes on Earth have detected many of these bursts, some of which come from galaxies billions of light years away, so we can actually see black holes being born.

rotational axis. The energies are so great that these particles are then magnetically beamed away from the black hole in visible jets that move at almost the speed of light. These jets, and the accretion discs they originate from, are incredibly bright, and when our line of sight is looking almost straight down one of these jets, we see a luminous object called a quasar. When we happen to be looking directly down the jet, it's even more luminous, and we call that a blazar. Regardless of what astronomers name it, the phenomenon is the same – a monster black hole that's spitting out a meal.

Some of the gas in the accretion disc does eventually find itself spiralling into the black hole. For anything approaching and crossing the event horizon, odd things happen. The warping of space-time by the mass of the black hole is so great here that something called gravitational time dilation occurs. As a person approaches the event horizon, time begins to run differently compared to the clocks belonging to observers who are watching from a distance – for example, us watching a black hole with our telescopes. A distant observer would see time stand still at the event horizon, and any astronaut crossing the event horizon would appear nearly frozen in time. The astronaut, however, would not perceive time slowing down; assuming they've somehow survived spaghettification, time will seem to proceed normally to them. It's just one of the weird consequences of general relativity.

And what of material that does fall irrevocably into a black hole? Where does it go, and can it ever come back out again? Stephen Hawking asked this question, and even made a famous bet about it. It turns out that black holes aren't truly black. Hawking became famous for the concept of Hawking radiation, which was the realisation that black holes can actually radiate particles, and even light. The secret lies in quantum field theory, which is a way of saying that on the quantum level, space is continuously fizzing with energy, spontaneously producing pairs of 'virtual' particles – one made of matter, the other of antimatter, such as a positron and an electron. They're described as 'virtual' because they usually instantly annihilate one another, as matter and antimatter do when they come into contact with one another, so they're not in existence for very long. But Hawking

DIFFERENT KINDS OF BLACK HOLE

A SMALL BLACK HOLE

Despite packing in more than 4 million times the mass of our Sun, the black hole at the centre of our galaxy is no larger than the Solar System.

THE CLOSEST BLACK HOLE

The nearest known black hole candidate is found in the triple star system HR 6819, which is 1,120 light years from Earth.

MOST MASSIVE BLACK HOLE

The heaviest of heavyweights is the supermassive black hole found in the quasar TON 618, with a mass 66 billion times greater than our Sun.

RUNAWAY BLACK HOLES

Galaxies often collide. When they do, their supermassive black holes also merge, which can give the product of the merger a kick, causing it to escape its galaxy.

MINIATURE BLACK HOLES

Some theories suggest that the Big Bang created a horde of micro black holes, with masses ranging from 100 millionths of a kilogram up to that of a small asteroid.

FAMOUS BLACK HOLES AND CANDIDATES


© NASA

CYGNUS X-1

Distance: 6,000 light years

Solar masses: 21.2

A stellar-mass black hole orbiting a blue supergiant star, from which the black hole is stealing gas that forms an accretion disc. It occasionally outbursts in X-rays.

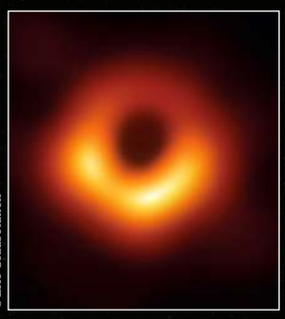

© NASA

SAGITTARIUS A*

Distance: 26,000 light years

Solar masses: 4.1 million

The supermassive black hole at the centre of our Milky Way. It's generally inactive, with only modest X-ray outbursts as it consumes small gas clouds.


© EHT Collaboration

MESSIER 87 BLACK HOLE

Distance: 54 million light years

Solar masses: 6.5 billion

The first black hole to be imaged right down to the event horizon, revealing the black hole's 'shadow' on the surrounding accretion disc.

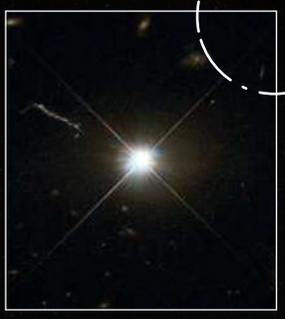

© SXS Lensing

GW150914 BLACK HOLE

Distance: 1.4 billion light years

Solar masses: 62

The product of the first black hole merger to be detected by gravitational waves formed when a 35-solar-mass black hole collided with a 30-solar-mass black hole. The extra three solar masses were converted into gravitational-wave energy.


© ESA/Hubble & NASA

3C 273

Distance: 2.4 billion light years

Solar masses: 886 million

The first quasar discovered, the black hole at its heart is hungrily guzzling gas, producing an incredibly bright accretion disc and a jet moving at almost the speed of light.

"SOME OF THE GAS IN THE ACCRETION DISC DOES EVENTUALLY FIND ITSELF SPIRALLING INTO THE BLACK HOLE"

Right: The Atacama Large Millimeter/submillimeter Array (ALMA) searches for signals of black holes

© ALMA

THE NETWORK THAT IMAGED A BLACK HOLE

These global telescopes blazed a trail for black hole imaging and revolutionised astrophysics

1 SOUTH POLE TELESCOPE
Location: Antarctica

2 ARIZONA RADIO OBSERVATORY'S SUBMILLIMETER TELESCOPE
Location: Arizona

3 JAMES CLERK MAXWELL TELESCOPE
Location: Hawaii

4 SUBMILLIMETER ARRAY
Location: Hawaii

5 LARGE MILLIMETER TELESCOPE
Location: Mexico

6 ATACAMA LARGE MILLIMETER/ SUBMILLIMETER ARRAY
Location: Chile

7 ATACAMA PATHFINDER EXPERIMENT
Location: Chile

8 VERY LONG BASELINE ARRAY
Location: New Mexico

9 ROBERT C. BYRD GREEN BANK TELESCOPE
Location: West Virginia

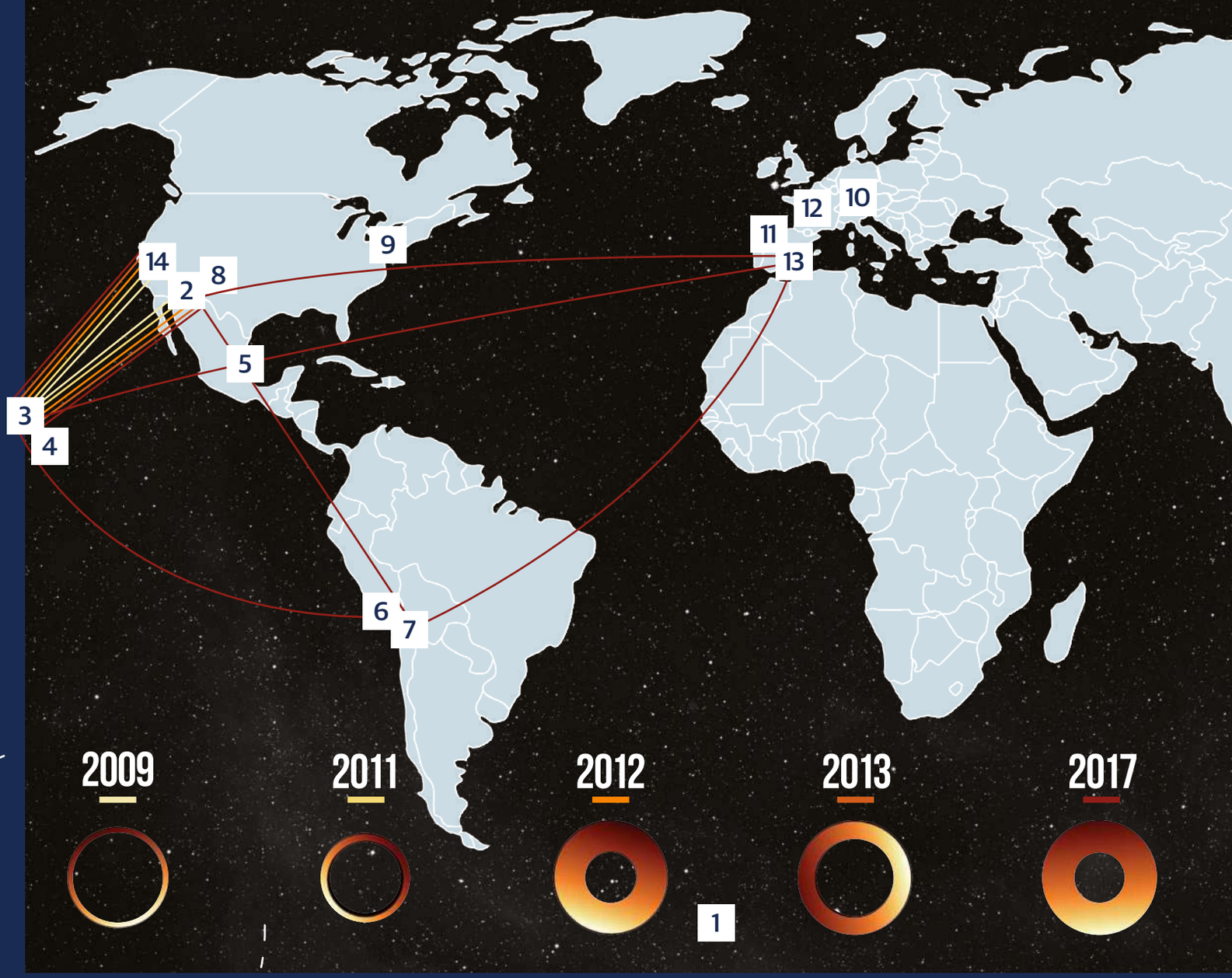
10 RADIO TELESCOPE EFFELSBERG
Location: Germany

11 YEBES OBSERVATORY
Location: Spain

12 NORTHERN EXTENDED MILLIMETER ARRAY
Location: France

13 INSTITUT DE RADIOASTRONOMIE MILLIMETRIQUE
Location: Spain

14 COMBINED ARRAY FOR RESEARCH IN MILLIMETER-WAVE ASTRONOMY
Location: California

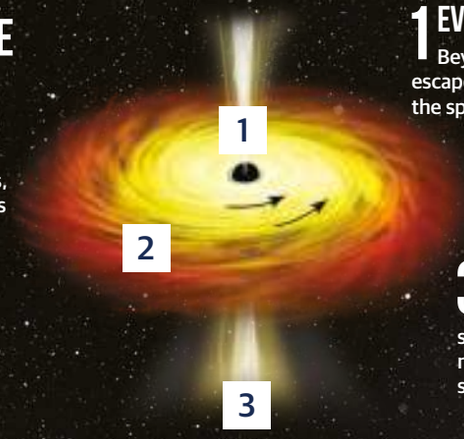


HOW THE EVENT HORIZON TELESCOPE WORKS

The planet-sized array used cutting-edge technology to reveal the edge of a black hole

CLOAKING DEVICE

Everything inside the event horizon of a black hole is forever hidden from view, because not even light can escape. But just outside this, the matter spiralling inwards shines brightly.



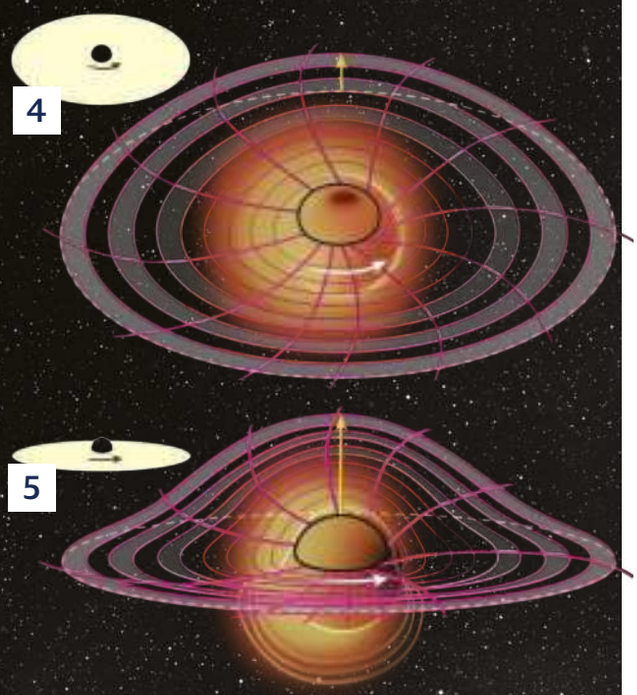
1 EVENT HORIZON
Beyond this radius, the escape velocity exceeds the speed of light.

2 ACCRETION DISC
Dust and gas gets accelerated almost to the speed of light.

3 POLAR JETS
Spinning black holes spew jets of ionised matter at relativistic speeds from each pole.

GRAVITATIONAL LENS

Light that passes close to the event horizon gets deflected, as if it was passing through a lens. This warps the circular accretion disc from our point of view.



4 FACE ON
If the accretion disc is nearly perpendicular to us, the gravitational lens effect is small.

5 EDGE ON
At oblique angles, the image is bent upwards, showing us behind the black hole.

GLOWING BANANA

Matter orbits so fast close to the black hole that the radiation shifts wavelength from one side to the other, making it brighter or darker to us.



6 BRIGHTER REGION
The side shifted towards detectable wavelengths appears brighter to us.

7 BLUESHIFT
Light moving towards Earth gets squashed towards shorter wavelengths.

8 REDSHIFT
Light moving away from Earth is stretched into longer wavelengths.

© Nicholas Forder

Right: Spiralling black holes on the path to a merger



© LIGO

realised that pairs of virtual particles coming into existence on the edge of the event horizon can be split up – one falls into the black hole, while the other, if it has enough energy, can race away into space and escape. Since the escaping particle has lost its antipartner, it doesn't annihilate, surviving to become a 'real' particle. Since the energy of the quantum field is drawn from the black hole's mass, the escaping particle is essentially running off with some of the mass of the black hole. Over the course of trillions and trillions of years, even the most supermassive black holes will begin to evaporate through the release of Hawking radiation.

Once a black hole evaporates, what happens to all the information of everything that went into it? This is the source of a great paradox, called the black hole information paradox, which became the focus of Hawking's famous bet with fellow physicists Kip Thorne and John Preskill. They would often make fun bets with one another, and in this particular case Hawking and Thorne bet Preskill that information inside a black hole is not preserved. In 2004 Hawking conceded the bet by agreeing that black holes do preserve information through Hawking radiation and gave Preskill a baseball encyclopaedia, 'made for the storage and retrieval of information'. Black holes fascinate us because they are so far out of our everyday experience, and there's still so much we don't know about them. When the Event Horizon Telescope took the very first image of a black hole's event horizon, around the supermassive black hole at the centre of the giant galaxy Messier 87, which is 53 million light years away, it made the front pages of newspapers. Who knows what new and bigger telescopes will discover about black holes in the future?



Giles Sparrow
Space science writer
Giles has degrees in astronomy and science communication and has written many books and articles on all aspects of the universe.



KILLER UNIVERSE

RELATIVELY SAFE IN OUR PROTECTIVE BUBBLE, SOME FORCES COULD END LIFE ON EARTH FOREVER. IS THE COSMOS OUT TO GET US?

Written by Nikole Robinson

While Earth isn't free of destructive impulses – natural disasters, climate change, radioactive rocks and deadly viruses, to name but a few – it's a relatively safe haven for humans among the stars, hence why humans have managed to evolve to live here so successfully. But leaving the confines of our planet's protective atmosphere, the universe gets a lot deadlier. As it turns out, space isn't the most welcoming place for us Earth dwellers, with many ways the universe could wipe us all out in just the blink of an eye.



© NASA/ESA

1 A GAMMA-RAY BURST MELTS THE ATMOSPHERE

Gamma-ray bursts (GRBs) are the most intense, high-energy radiation events in the universe, thought to be produced from explosive cosmic events like hypernovae, black hole formation and colliding neutron stars. Though these beams typically last just a few seconds, they release 10 billion years of solar energy in this tiny timeframe.

We've only observed GRBs in distant galaxies so far, but there's no reason the same physics couldn't apply in our Milky Way. If a nearby event triggered such a burst, and the electromagnetic beam was directed straight at our planet, we wouldn't feel any immediate effect. However, the intensity of the radiation would strip away the ozone layer of our atmosphere in mere seconds, leaving us vulnerable to cosmic rays and the full ultraviolet radiation that the Sun sends our way. And because of the split-second nature of GRBs, it would be nigh impossible to predict when one could strike us. It also might not be the first time: a local GRB is one theory put forward to explain the Late Ordovician mass extinction – one of Earth's five major extinction events – which took place around 450 million years ago, wiping out 85 per cent of species in our primitive oceans.

2 MURDEROUS MAGNETARS

When a star dies, if it falls in a certain mass range it can collapse into a neutron star, a super-dense, city-sized stellar corpse. These cosmic cadavers can have extreme magnetic fields – up to 1,000 trillion times that of Earth – and these are dubbed magnetars. Out of about 3,000 known neutron stars in our galaxy, 31 are confirmed to be magnetars, making them quite the rarity. However, if Earth were somehow to come within 1,000 kilometres (621 miles) of one of these magnetic monstrosities, we would all be doomed. The fatal attraction of its magnetic field would start to destabilise our atoms, ripping the electrons from everything on Earth and reducing all life to ion clouds. As well as having the most intense magnetic fields in the universe, these stellar remnants also produce a great deal of radiation across the electromagnetic spectrum, and may even be a source of potentially deadly GRBs.



© Getty

"IF ANYTHING WERE TO UPSET THIS BALANCE, OUR STAR COULD START TO DIE, WITH EARTH FOLLOWING SUIT"



Source: Wikipedia Commons © Fsgregs

Above: Artist's impression of a beam of gamma radiation firing into the cosmos

Left: A Sun-scorched Earth would be left uninhabitable

Right: Magnetars are extremely powerful neutron stars

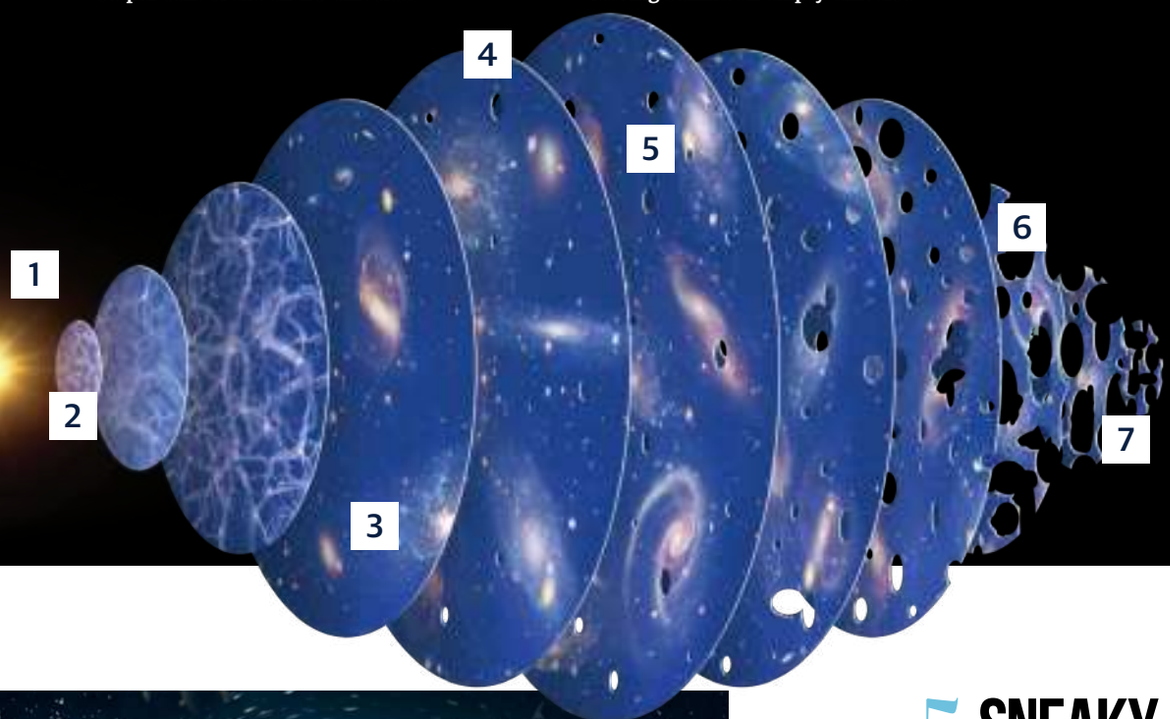
3 PREMATURE DEATH OF THE SUN

The Sun is a ticking nuclear bomb, and it will take Earth and the other inner planets with it when it dies. As it runs out of hydrogen to fuse, it will cool and swell into a red giant, sending out waves of intense radiation as it fuses heavier elements within before shrinking into a white dwarf after these alternative fuel sources also run dry. Approximately halfway through its stellar life cycle and not predicted to run out of fuel for another 5 billion years – at which point we will either already be extinct or have become an interplanetary species – unknown processes or interference could shorten the life of our star and cause it to swell sooner or more rapidly than predicted. Our host is currently in equilibrium, with the inward force of gravity balanced by the outward force of thermal pressure from the nuclear fusion that powers it. But if anything were to upset this balance, our star could start to die, with Earth following suit.

4 THE BIG RIP TEARS EVERYTHING APART

When astronomers first tried to measure the expansion of the universe using the Hubble Space Telescope in 1998, they expected it to have slowed down since the Big Bang blasted everything into existence 13.8 billion years ago. But they were surprised to find out expansion is actually accelerating, with galaxies moving away from each other at an ever-quicker pace. Though we still don't know for sure what's causing the increase in speed, the blame has been put on dark energy, a mysterious and invisible repellant force which makes up around 68 per cent of the entire universe.

Some scientists think that dark energy's influence is increasing, and that at some point in the future the expansion-accelerating force could completely overpower the forces that hold everything together, from your atoms to the biggest galaxies. First it will overpower gravity – the weakest of the four fundamental forces – tearing apart galaxies, then the stellar systems within them. Eventually it will affect the strong nuclear force which holds together the protons and neutrons that make up our very atoms, tearing up the building blocks of everything and leaving behind an empty universe.



1 BIG BANG
The universe began from an infinitesimally small point 13.8 billion years ago: a singularity.

2 INFLATION
Our universe expanded rapidly, increasing in size by up to 100 times or more.

3 FIRST STARS
The first stars formed 300 million years after the Big Bang, with gravity pulling them together to form galaxies on a local scale.

4 ACCELERATING
Space-time is being pulled apart at a faster and faster rate.

5 GRAVITY
Once the expansion of the universe reaches a certain speed, gravity will no longer be able to hold objects together, and the universe will head to its doom.

6 TORN APART
Eventually space-time will be expanding so fast that galaxies will be pulled apart, followed by stars and planets.

8 THE BIG RIP
Everything will move away from everything else so quickly that none of the forces will be able to keep atoms together, tearing everything apart.

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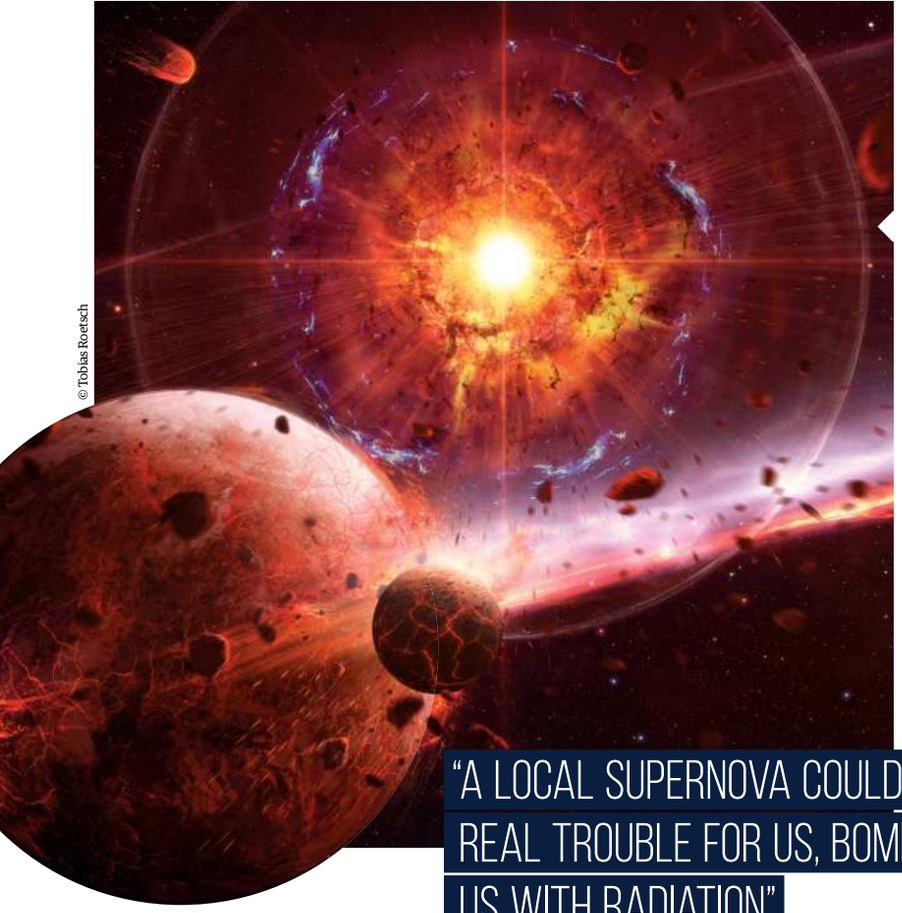
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Above: Concept of the expansion of the universe and the Big Rip

Left: Small black holes would be extremely hard to identify

5 SNEAKY STELLAR-MASS BLACK HOLE

While we can be safe in the knowledge that the supermassive black hole at the centre of the Milky Way is unable to gobble up our whole galaxy – and we're safely sitting 26,000 light years from the galactic centre where it dwells – smaller, sneakier black holes could come close enough to start pulling in the Solar System if one headed our way. Stellar-mass black holes are super-dense singularities with masses less than 100 times that of the Sun. There are thought to be around 100 million of these dinky devourers in the Milky Way, though most discovered so far have been found in binary pairs. When they have a partner feeding them material, they are much easier to detect, since we can see their interactions. But a hungry lone roamer with the right mass would be practically undetectable until it started turning our Sun into spaghetti. As this would be our first hint at its approach, we'd just have to watch the Sun be slowly swallowed and accept our fate.



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Left: The force of a supernova could shatter nearby planets

6 LOCAL SUPERNOVA

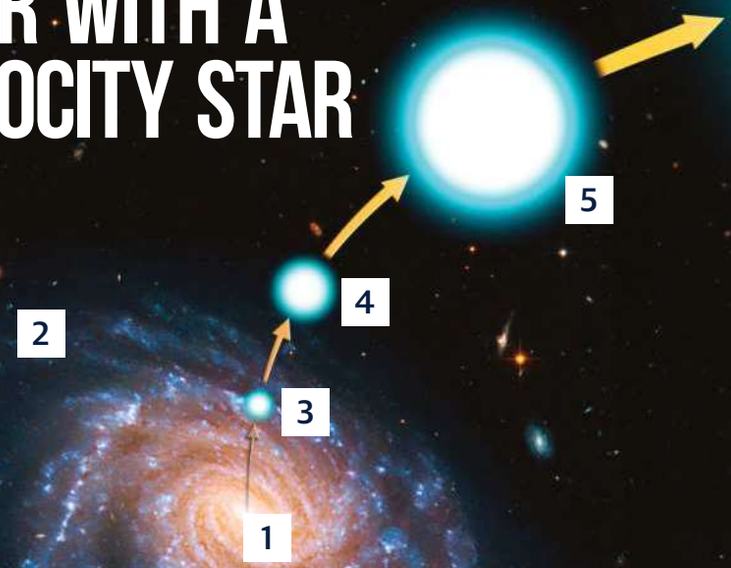
When a large enough star dies, it goes out with a bang, spreading material and radiation into the cosmos. Though astronomers have calculated that Milky Way supernovae should occur every 50 to 100 years on average, we seem to have waited a while, and only five naked-eye supernovae exist in historical records. But how close would one have to be to affect Earth? According to NASA, within about 50 light years. We're safe from this threat for now, as the nearest supernova candidate to us, IK Pegasi B, is 150 light years away. Betelgeuse, a red giant star astronomers expectantly watch hoping for a spectacular supernova show, is 642 light years away – enough for an explosion to be visible in our daytime skies, but posing no harmful effects. We're lucky in that regard, because a local supernova could spell real trouble for us, damaging the atmosphere and bombarding us with radiation, likely triggering a mass extinction event.

"A LOCAL SUPERNOVA COULD SPELL REAL TROUBLE FOR US, BOMBARDING US WITH RADIATION"

7 ENCOUNTER WITH A HYPERVELOCITY STAR

Stars move at different speeds as they travel around our galaxy. For example, our Sun travels around the galactic centre at about 220 kilometres (137 miles) per second, completing an orbit in around 230 million years. But closer to the centre, orbits get a lot quicker. The very fastest stars beat the Sun's speed at least tenfold, achieving escape velocity and sometimes becoming unbound from the Milky Way. These so-called hypervelocity stars are thought to have been accelerated by close encounters with Sagittarius A*, our galaxy's supermassive black hole, or by a former binary partner going supernova.

Because of their immense speeds, these stars don't follow typical orbits and can make their own paths – it's also suspected that some may enter the Milky Way from dwarf galaxies like the Large Magellanic Cloud (LMC). It's highly improbable because of the vastness of space, but if a hypervelocity star passed too close to our Solar System on its way out, it could cause some serious disruption, either by disturbing the Oort Cloud and sending thousands of comets into the Solar System or destabilising the orbit of Earth itself.



© NASA/ESA

HOW HE 0437-5439 BECAME A LOOSE CANNON

1 CUT LOOSE
About 100 million years ago, the star system's more distant component was pulled towards Sagittarius A*.

2 DANGEROUS ORBIT
The stellar triplets probably formed billions of years ago in an orbit close to the Milky Way's central black hole.

3 MERGING STARS
The heavier of the two surviving stars evolved more quickly, engulfing its partner, and the two merged.

4 OUT OF THE CORE
The close binary was flung towards intergalactic space fast enough to escape our galaxy's gravitational pull.

5 INTERGALACTIC REFUGEE
HE 0437-5439 is now 200,000 light years from the core or our galaxy, headed for a close approach with the LMC.



"THIS HIGGS FIELD PERMEATES ACROSS THE ENTIRETY OF SPACE, INVISIBLE BUT EVERYWHERE."

8 A CHANGING HIGGS FIELD

A subatomic particle confirmed at the Large Hadron Collider in 2012, the Higgs boson, along with the associated Higgs field, is what gives every particle in the universe mass. This Higgs field permeates across the entirety of space, invisible but everywhere. A particle which moves through this field with ease, like a neutrino, has a lower mass than one which encounters more resistance. But the Higgs' own mass is capable of changing, and that would alter the very universe through the strength of the Higgs field. The field is understood to be metastable, unchanging, but potentially not at its lowest possible energy level, meaning we currently exist in a false vacuum.

It would only take a single Higgs boson somewhere in the universe collapsing to a lower energy state to change the mass of all subatomic particles and the very physics of the universe, triggering catastrophic vacuum decay. If this were to happen, a bubble of true vacuum could radiate outwards from the source at the speed of light at any time, and we wouldn't see it coming. We'd just be obliterated without warning, and the universe might never again have the right conditions to support life, or anything.

HIGGS: WHY MATTER HAS MASS

Particles may be more massive than one another because they feel the Higgs field differently



MEETING THE HIGGS FIELD

The Higgs field occurs everywhere and gives matter particles mass. We can envision the Higgs field as a group of evenly separated balls.

ENTER ORDINARY MATTER

When a particle of ordinary matter moves through the Higgs field, the field becomes excited and forms Higgs bosons, which cluster around the particle and provide it with mass.

HIGH-SPEED PHOTONS

Particles can move through space without interacting with the Higgs field. They don't gain any mass from Higgs bosons and remain massless. A photon is one such particle.

© Tobias Roetsch

Left: The Higgs boson is an elementary particle

Below: A waterless, dead Earth would be much more Martian

9 LOSS OF EARTH'S MAGNETIC FIELD

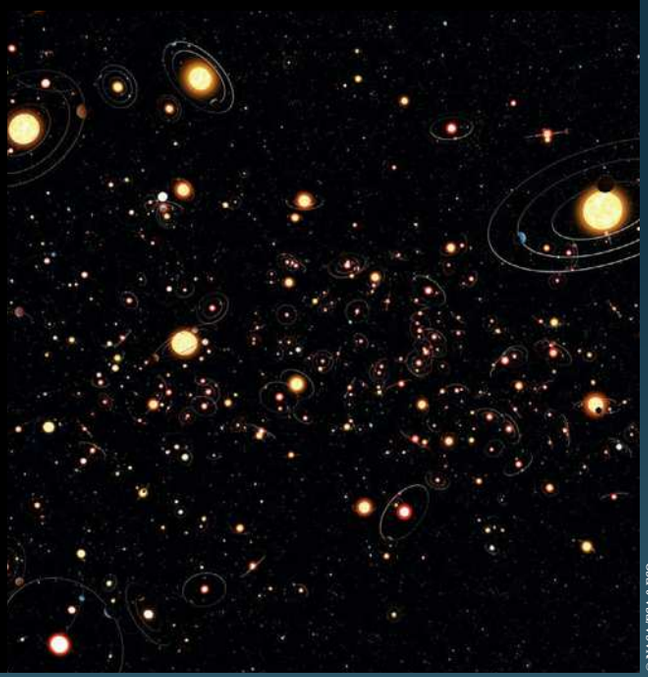
As well as our atmosphere acting as an oxygen-filled shield, Earth's magnetic field plays a critical role in protecting our planet and all its inhabitants from the dangers of cosmic radiation, redirecting the solar wind and radiation from other sources away from the surface. The magnetosphere is a result of Earth's rotation – as molten iron-nickel swirls around the solid inner core, a giant dynamo is created, powering this global field. But it's in a constant state of flux, with its strength varying over time. It also appears to be cooling, which spells trouble for the future of our planet. A weaker magnetic field isn't able to protect us from radiation that well, meaning we'd be under threat by any high doses sent our way by solar events like flares and coronal mass ejections, or from more distant high-energy events. The constant bombardment of the solar wind could also affect our atmosphere, stripping away our planetary protection even further. In fact, many scientists believe this is how Mars ended up as a desolate dust ball. Perhaps we await the same destiny.



© Getty

10 WE'RE NOT PAST THE GREAT FILTER

While aliens seeking us out could end badly, finding even simple signs of life in the universe could also be problematic. It's estimated our galaxy hosts 100 billion planets, so why haven't we found any with signs of life? It's been posited that there may be filters along the evolutionary scale that prevent life from reaching certain stages, and that a 'Great Filter' prevents any species from reaching spacefaring status. The big question is whether we're past this point, or not. If we are, we could be the very first species to make it, explaining the silence of space. As the most advanced, intelligent species on our own planet, it's not too hard to imagine us being farther ahead going further afield. However, if this filter still lies ahead, humanity is doomed. Some hypothesise that the Great Filter could be a consequence of advancing technology, and that any species capable of developing its planet is also set to destroy itself, so perhaps we're already on this path to destruction.



© NASA/ESA & ESO

Above: Planets are widespread, so why haven't we found signs of life yet?

Below: We'd have no defence against advanced alien technology

11 HOSTILE ALIENS

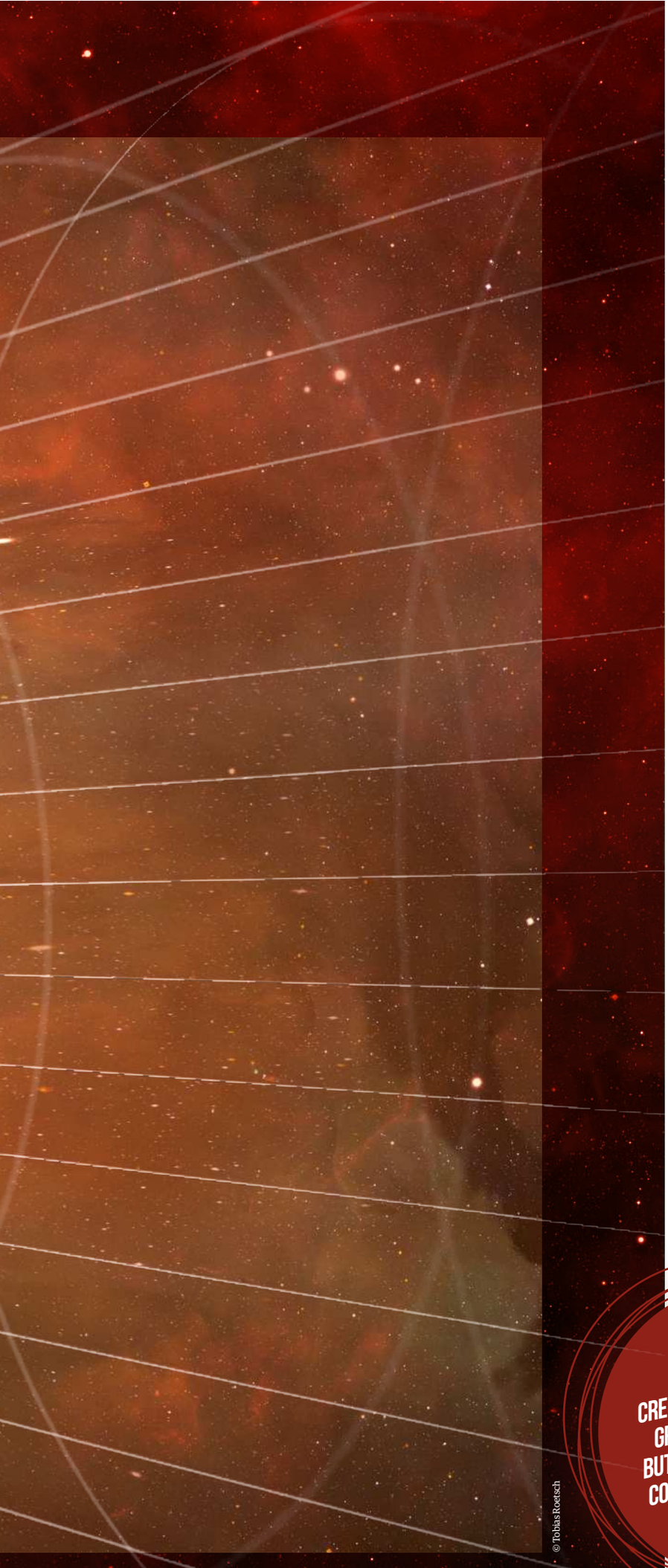
While humanity has spent decades searching for alien signals and signs of life from elsewhere in the galaxy, there's a chance that extraterrestrials could find us first, with disastrous results. If an advanced civilisation were to drop in above our planet unexpectedly, it's likely that their technology would be much more advanced than ours, including weaponry. As famously said by physicist Steven Hawking: "Such advanced aliens would perhaps become nomads, looking to conquer and colonise whatever planets they can reach." If these visitors had bad intentions – or if they were to deem us a threat to the galaxy – they could destroy us all with harmful technology that humanity hasn't even imagined yet. They may also want to harvest our planet's resources for themselves, or be looking for a new habitable home after having to leave their own world.

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BLACK HOLES

HOW DO WE KNOW THEY'RE REAL?



© Tobias Roetsch

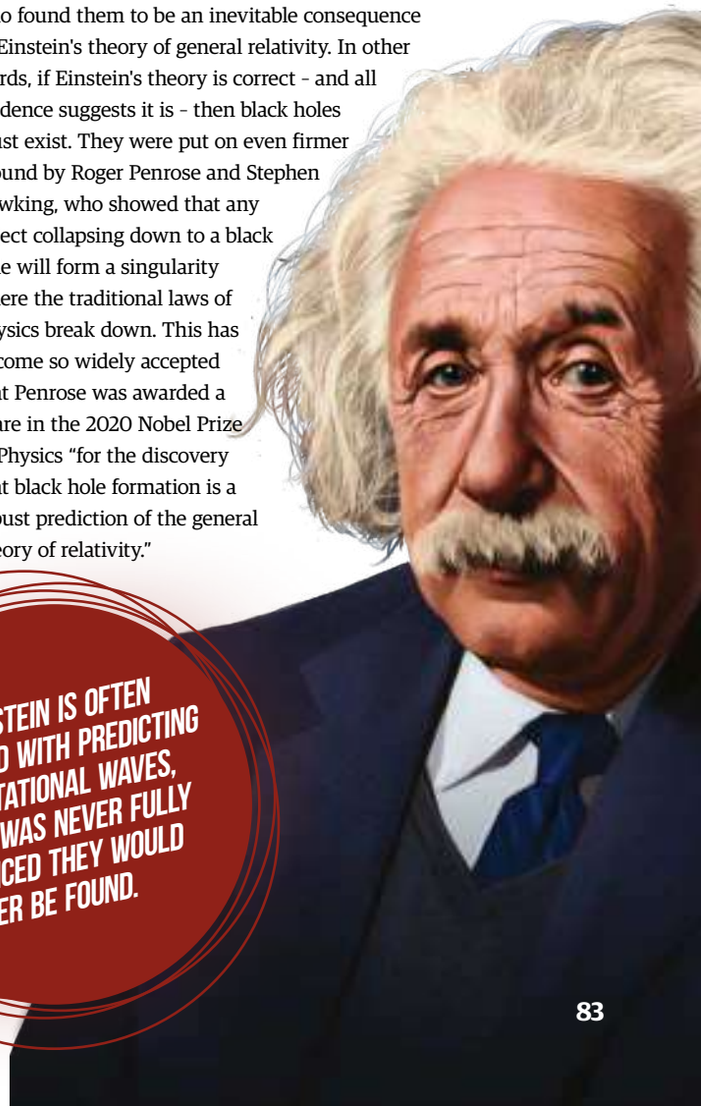
Reported by Andrew May

ONCE PURELY THEORETICAL, NOW THERE'S HARD EVIDENCE THESE HIGH-GRAVITY OBJECTS EXIST

Of all the far-out concepts in astronomy, black holes may be the weirdest. A region of space where matter is so tightly packed that nothing – not even light itself – can escape, these dark behemoths present a pretty terrifying prospect. With all the normal rules of physics breaking down inside them, it's tempting to dismiss black holes as the stuff of science fiction. Yet there's plenty of evidence – both direct and indirect – that they really do exist in the universe.

EINSTEIN'S 'ROBUST PREDICTION'

As a theoretical possibility, black holes were predicted in 1916 by Karl Schwarzschild, who found them to be an inevitable consequence of Einstein's theory of general relativity. In other words, if Einstein's theory is correct – and all evidence suggests it is – then black holes must exist. They were put on even firmer ground by Roger Penrose and Stephen Hawking, who showed that any object collapsing down to a black hole will form a singularity where the traditional laws of physics break down. This has become so widely accepted that Penrose was awarded a share in the 2020 Nobel Prize in Physics "for the discovery that black hole formation is a robust prediction of the general theory of relativity."



EINSTEIN IS OFTEN CREDITED WITH PREDICTING GRAVITATIONAL WAVES, BUT HE WAS NEVER FULLY CONVINCED THEY WOULD EVER BE FOUND.



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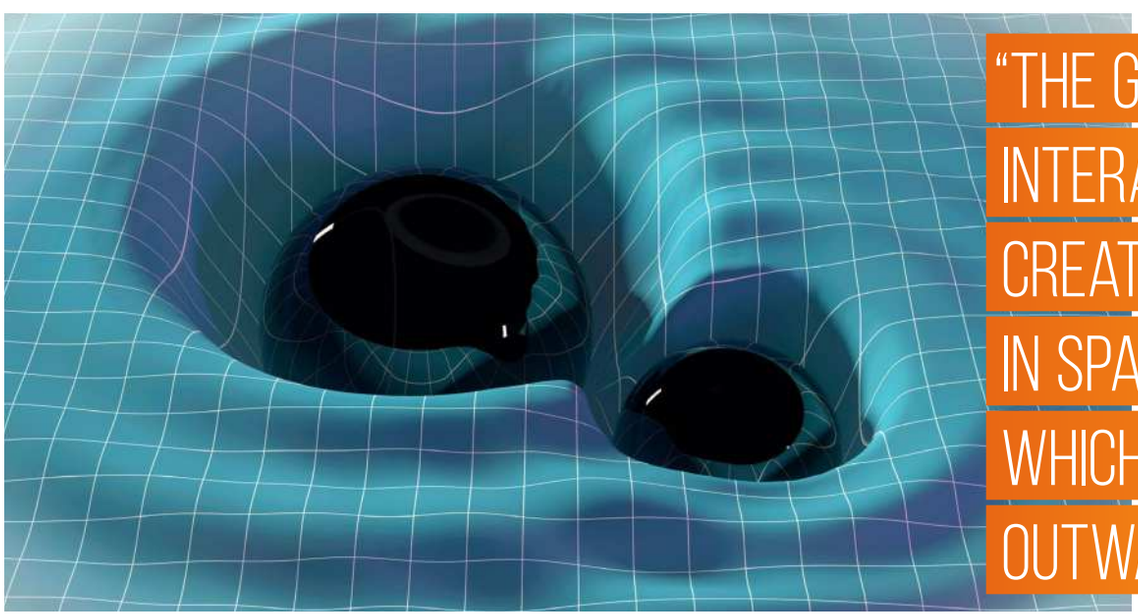
THEY CAN EMIT GRAVITATIONAL WAVES

Black holes don't always exist in isolation; sometimes they occur in pairs, orbiting around each other. When they do, the gravitational interaction between them creates ripples in space-time, which propagate outwards as gravitational waves. With observatories like the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo, we now have the ability to detect these waves. The first discovery, involving the merger of two black holes, was announced back in 2016, and many more have been made since then. As detector sensitivity improves, other wave-generating events besides black hole mergers are being discovered, such as a crash between a black hole and a neutron star, which took place way beyond our own galaxy at a distance of 650 million to 1.5 billion light years from Earth.

GAMMA-RAY BURSTS ARE EVIDENCE

In the 1930s, Indian astrophysicist Subrahmanyan Chandrasekhar looked at what happens to a star when it has used up all its nuclear fuel. The end result depends on the star's mass. If that star is really big, say, 20 solar masses, then its dense core – which may itself be three or more times the mass of the Sun – collapses all the way down to a black hole. The final core collapse happens incredibly quickly, in a matter of seconds, and it releases a tremendous amount of energy in the form of a gamma-ray burst. This burst can radiate as much energy into space as an ordinary star emits in its entire lifetime. And telescopes on Earth have detected many of these bursts, some of which come from galaxies billions of light years away, so we can actually see black holes being born.

GAMMA-RAY BURSTS WERE DISCOVERED ACCIDENTALLY IN 1967 BY A MILITARY SATELLITE DESIGNED TO MONITOR NUCLEAR WEAPON TESTS.



© Getty

"THE GRAVITATIONAL INTERACTION CREATES RIPPLES IN SPACE-TIME, WHICH PROPAGATE OUTWARDS"



THEY'RE A MASSIVE X-RAY SOURCE

The first observational evidence for a black hole emerged in 1971, and this too came from a binary star system within our own galaxy. Called Cygnus X-1, the system produces some of the universe's brightest X-rays. These don't emanate from the black hole itself, or from its visible companion star, which is enormous at 33 times the mass of our own Sun. Instead, matter is constantly being stripped from the giant star and dragged into an accretion disc around the black hole, and it's from this accretion disc that the X-rays are emitted. As was the case with HR 6819, astronomers used observed star motion to estimate the mass of the unseen object in Cygnus X-1. The latest calculations put the dark object at 21 solar masses, concentrated into such a small space that it couldn't be anything other than a black hole.

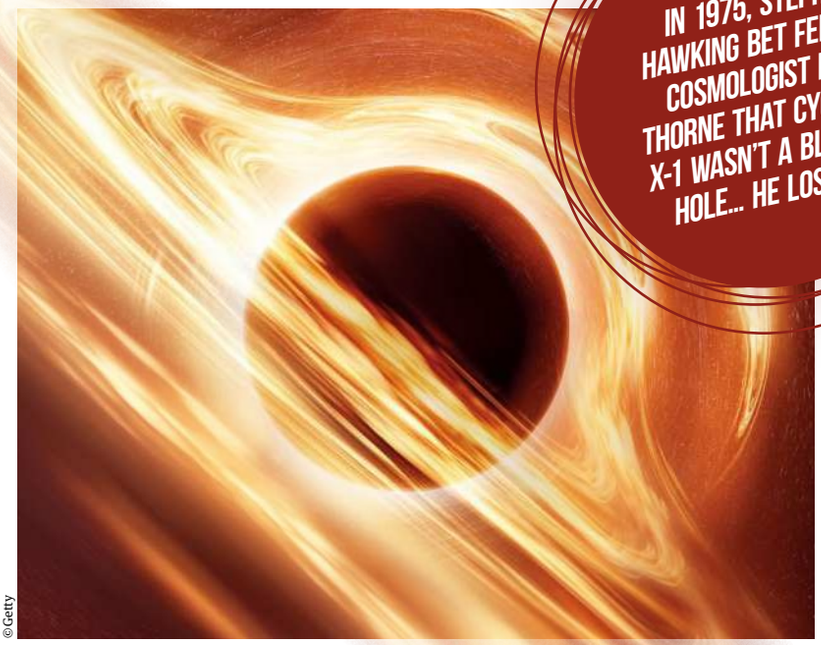
©NASA/ESA

REINHARD GENZEL AND ANDREA GHEZ SHARED THE 2020 NOBEL PRIZE FOR DISCOVERING A SUPERMASSIVE BLACK HOLE IN THE MILKY WAY GALAXY.

THEY HAVE INVISIBLE COMPANIONS

There's one sure-fire way to detect these dark beasts, and that's through their gravitational effects on other stars. When observing the ordinary-looking binary system known as HR 6819 in 2020, astronomers noticed oddities in the motion of the two visible stars that could be explained only if there was a third totally invisible object there. When they worked out its mass – at least four times that of the Sun – the researchers knew there was only one possibility left. It had to be a black hole – the closest yet discovered to Earth, a mere thousand light years away inside our home galaxy.





© Getty

IN 1975, STEPHEN HAWKING BET FELLOW COSMOLOGIST KIP THORNE THAT CYGNUS X-1 WASN'T A BLACK HOLE... HE LOST.

SUPERMASSIVE BLACK HOLES

In addition to black holes created through stellar collapse, evidence suggests that supermassive black holes, millions or even billions of solar masses, have been lurking in the centres of galaxies since early in the history of the universe. In the case of so-called active galaxies, the evidence for these heavyweights is spectacular. The central black holes in these galaxies are surrounded by accretion discs that produce intense radiation at all wavelengths of light. We also have evidence that our own galaxy has a black hole at its centre. That's because we see the stars in that region whizzing around so fast – up to eight per cent of the speed of light – that they must be orbiting something extremely small and massive.

WE'VE SEEN SPAGHETTIFICATION AT WORK

"YOU GET STRETCHED OUT INTO THIN STRANDS BY THE BLACK HOLE'S EXTREME PULL"

Another piece of evidence for the existence of black holes is spaghettification. What, you might wonder, is spaghettification? It's what happens when you fall into a black hole, and it's pretty self-explanatory. You get stretched out into thin strands by the black hole's extreme gravitational pull. Luckily, that's not likely to happen to you or anyone you know, but it may well be the fate of a star that wanders too close to a supermassive black hole. In October 2020, astronomers witnessed this shredding – or at least the flash of light – from a hapless star as it was ripped apart. Fortunately, this spaghettification didn't happen anywhere near Earth, but instead in a galaxy 215 million light years away.



© Adrian Mann



THE LARGEST KNOWN BLACK HOLE, DEEP INSIDE THE SHAPLEY SUPERCLUSTER, IS ESTIMATED AT ALMOST 80 BILLION SOLAR MASSES.

THERE'S A DIRECT IMAGE

So far we've had plenty of compelling indirect evidence for black holes: bursts of radiation, gravitational waves or dynamical effects on other bodies that couldn't have been produced by any other object known to science. But the final clincher came in April 2019 in the form of a direct image of the supermassive black hole at the centre of active galaxy Messier 87. This stunning photo was taken by the Event Horizon Telescope, which consists of a large network of telescopes scattered all over the world rather than a single instrument. The more telescopes that can participate, and the more widely spaced they are, the better the final image quality. The result clearly shows the dark shadow of the 6.5-billion-solar-mass black hole against the orange glow of its surrounding accretion disc.

© Getty

THERE'S A BARRIER AROUND THE MILKY WAY'S CENTRE

Astronomers discover an enormous, bizarre feature separating the centre of the Milky Way from the cosmic ray sea

Reported by Brandon Specktor

The centre of the Milky Way may be even more bizarre than astronomers thought. A team of researchers from the Chinese Academy of Sciences in Nanjing investigated a map of radioactive gamma rays – the highest energy form of light in the universe, which can arise when extremely high-speed particles called cosmic rays crash into ordinary matter – blasting in and around the centre of our galaxy.

The map revealed that something near the centre of the galaxy appears to be accelerating particles to mind-blowing speeds – very near the speed of light – and creating an abundance of cosmic rays and gamma rays just outside the galactic centre.

However, even as the galactic centre blows a constant storm of high-energy radiation into space, something near the Milky Way's core prevents a large portion of cosmic rays from other parts of the universe from entering.

The researchers described the effect as an invisible 'barrier' that is wrapped around the galactic centre and is keeping the density of cosmic rays there significantly lower than the baseline level seen throughout the rest of our galaxy. In other words, cosmic rays can get out of the galactic centre, but have a much harder time getting in.

The centre of our home galaxy is located about 26,000 light years from Earth in the constellation of Sagittarius. It's a dense and dusty place, holding more than 1 million times as many stars per light year as the entire Solar System, all wrapped around a supermassive black hole with about 4 million times the mass of the Sun.

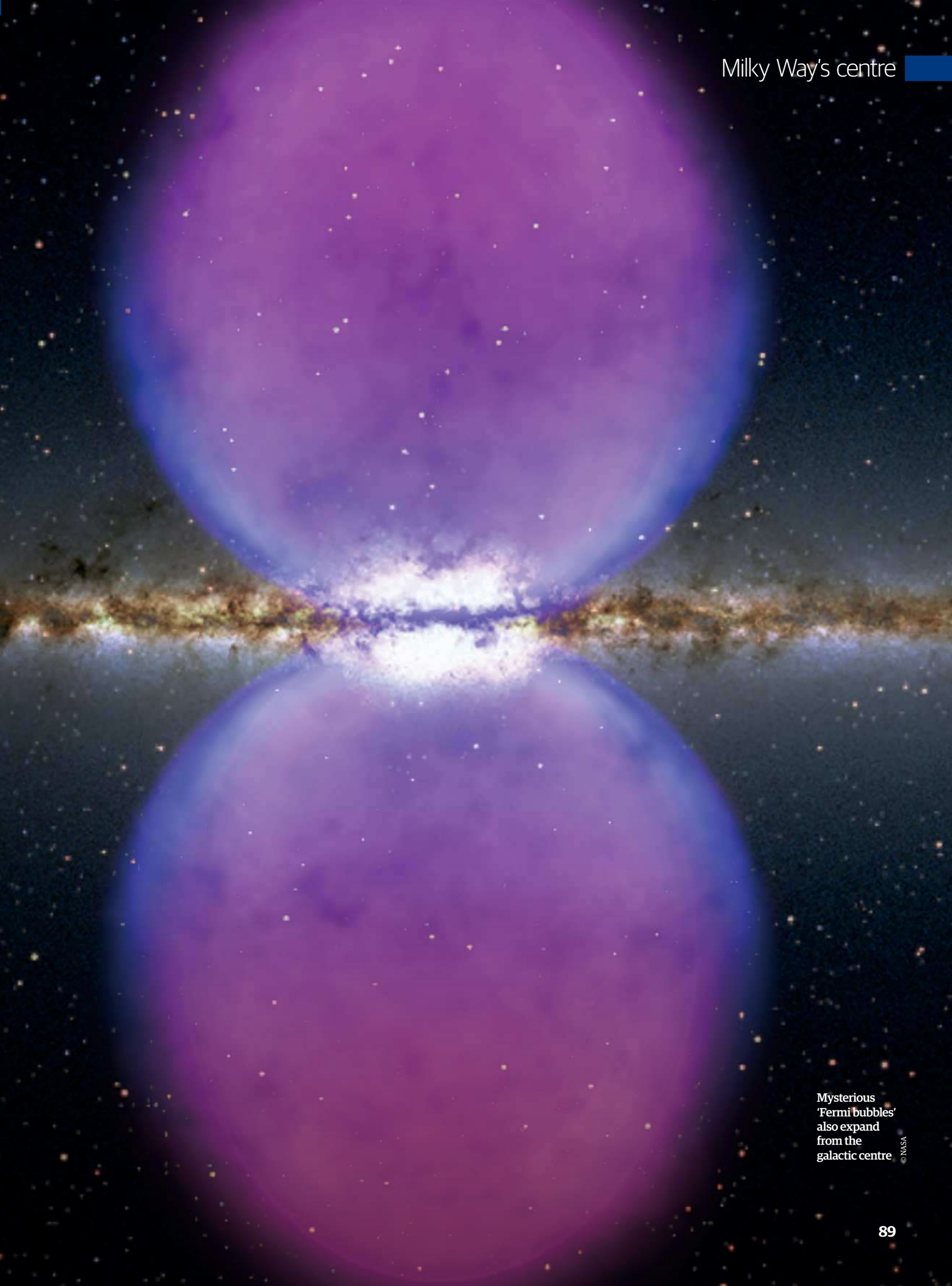
Scientists have long suspected this black hole, named Sagittarius A* (Sgr A*), or perhaps some other object at the galactic centre, is accelerating protons and electrons to near light speed, creating cosmic rays that beam throughout our galaxy and onward into intergalactic space. These rays propagate through the magnetic fields of our galaxy, creating an ocean of high-energy particles that's roughly uniform in density throughout the entire Milky Way. This steady soup of particles is called the cosmic ray sea.

The researchers compared the density of cosmic rays in this sea to the density of cosmic rays within the galactic centre. Cosmic rays cannot be seen directly, but scientists can find them in gamma-ray maps of space, which effectively show where cosmic rays have collided with other types of matter.

> "COSMIC RAYS CAN GET OUT OF THE GALACTIC CENTRE, BUT HAVE A MUCH HARDER TIME GETTING IN"

Using data from the Fermi Large Area Telescope, the team confirmed that something in the galactic centre is indeed acting as a giant particle accelerator, shooting cosmic rays out into the galaxy. Possible culprits include Sgr A* – as black holes could theoretically shoot certain particles into space even as they gobble up everything else around them – the remnants of ancient supernovae or even strong stellar winds from the many stars in the galactic centre.

But the map also revealed the mysterious 'barrier', a clear point where the density of cosmic rays drops off significantly at the edge of the galactic centre. The source of this phenomenon is harder to pinpoint, but it may involve the jumble of magnetic fields near our galaxy's dense core. For example, dense clouds of dust and gas near the galactic centre could collapse onto themselves, compressing the magnetic fields there and creating a cosmic-ray-proof barrier. Or perhaps stellar winds from the myriad of stars at the galactic centre are pushing back against the cosmic ray sea, much as the solar wind does.



Mysterious 'Fermi bubbles' also expand from the galactic centre

© NASA

MYSTERIES OF THE UNIVERSE

WHERE HAVE THESE GIANT FILAMENTS COME FROM?

Mysterious magnetic filaments have been found at the heart of the Milky Way, but astronomers are still trying to discover their origin

Reported by David Crookes

In 1984, astronomer Farhad Yusef-Zadeh was observing the night sky when he spotted something rather unusual that stopped him in his tracks. He had been working on his PhD at Columbia University, attempting to figure out the nature of compact sources. But along with colleague Don Chance and University of California at Los Angeles professor Mark Morris, he helped identify three large arcs some 150 light years long.

At first they couldn't believe what they were seeing. Though the existence of filaments had been proposed by Swedish plasma physicist Hannes Alfvén and later proven, nobody other than him thought these one-dimensional strands would stretch to such lengths. Even Yusef-Zadeh, now of Northwestern University in Illinois, wasn't trying to prove the existence of filaments. "We were trying to figure out the nature of compact sources in this region," he says.

But here was a small team staring at potential proof – a discovery made using the Very Large Array (VLA), the world's most widely used radio telescope, located 80 kilometres (50 miles) west of Socorro, New Mexico. "It was an accident," Yusef-Zadeh recalls. "It turned out the compact sources – expected to be HII regions associated with star formation – were peaks of extended filamentary structures. But since this type of structure hadn't been seen before, we were suspicious that they were real."

Left: As well as being able to see the bubble discovered in 2018, this image shows the black hole Sagittarius A*, as well as the magnetic filaments

© SARAO

MAGNETIC FILAMENTS BY NUMBERS

1,000
Number of magnetic strands found at the Milky Way's centre

TEN
times more than previously discovered

150
Length in light years

1984
Year they were first observed

200
Hours spent surveying the region using the MeerKAT telescope array

20
Separate radio observations combined

25,000
Distance of the filaments from Earth in light years

0.5
Space between the filaments in parsecs

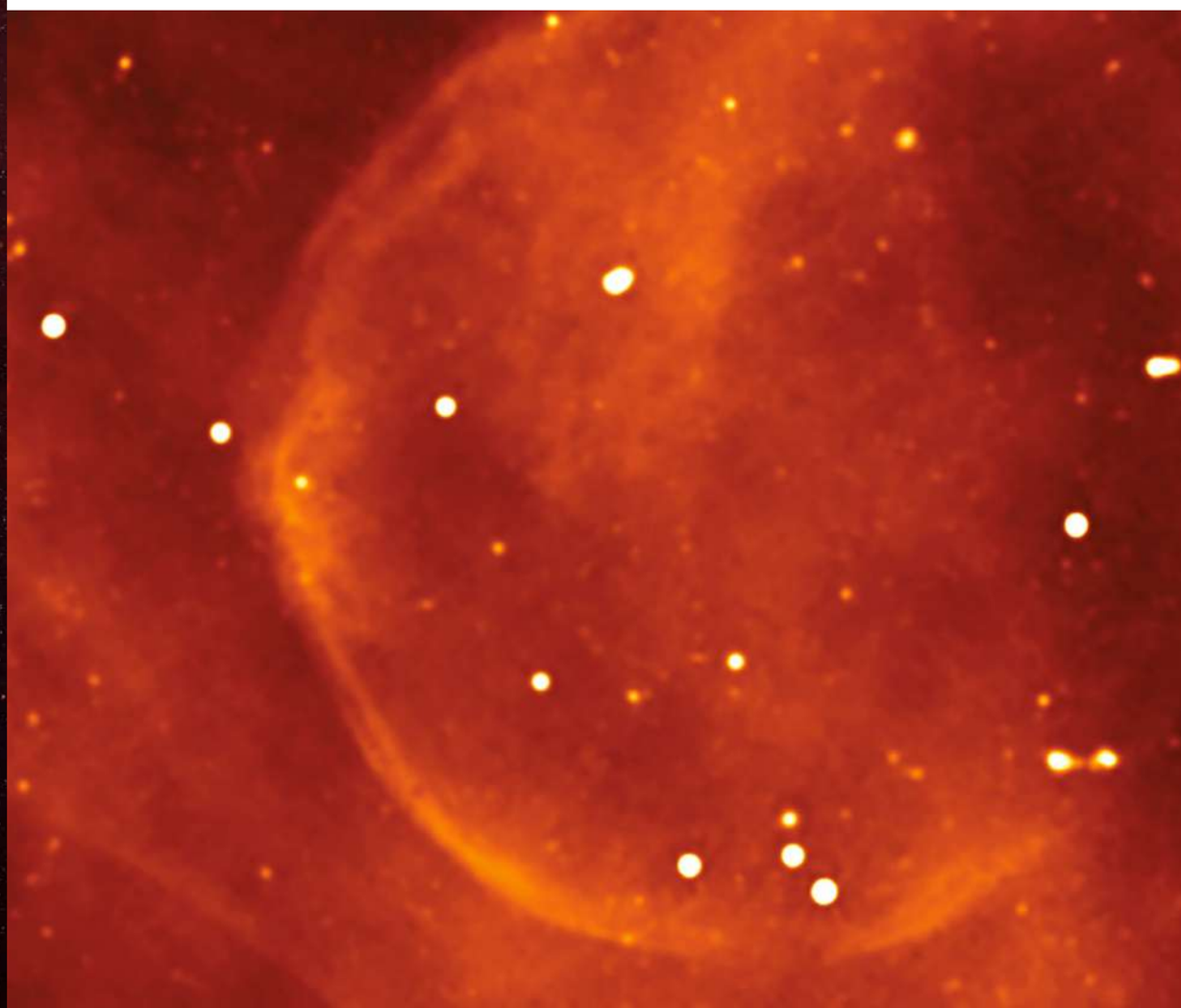
The trio of parallel filaments were narrow – just a couple of light years thick – but given their prominence and their surprising discovery, they also demanded extra attention. Indeed, the astronomers continued with their work, gathering more evidence until there was no doubt in their minds. "We eventually confirmed our result by detecting the same filaments at multiple frequencies," Yusef-Zadeh explains, a task that finally ruled out bad data. The discovery had a huge effect, not only on science but on Yusef-Zadeh personally. "The contrast in size scale between compact sources and what we found was huge," he says. "The direction of my thesis topic changed completely after detecting radio filaments, so I lost a couple of years of work based on my earlier study."

Even so, over the following years, more of these filaments were discovered using the VLA, leaving astronomers ever more intrigued and yet baffled at the same time. "The filaments were mainly directed perpendicular to the galactic plane," says Yusef-Zadeh. "As such there were no obvious sources powering the filaments, and the morphology was unusual." It has spawned a long-term mystery that continues to preoccupy Yusef-Zadeh and many others to this day. "There were just no clues as to the origin of these filaments," Yusef-Zadeh laments. But he may well be on the verge of a breakthrough in finally discovering just what is causing them, and he's getting very excited at the prospect.

Over time, the filaments have been interpreted as cosmic-ray electrons gyrating the magnetic field at close to the speed of light. Astronomers believed they would provide an insight into the structure of magnetic fields at the heart of the Milky Way, but the question is less what they are and more how they came to be. "There are now a couple dozen theoretical models for the origin of the filaments, but there's no model that's accepted by everyone," Yusef-Zadeh says.

In that sense the answer remains very much up in the air, and it's still open to debate. "There were models related to stellar sources powering preexisting magnetic structures or there were theories related to turbulent conditions of the interstellar medium in the nucleus of our galaxy," he says. One of the problems has been having too few filaments to study – numbers that have been counted in the dozens. It has long made it difficult to draw any clear conclusions, and that's proven to be mightily frustrating.

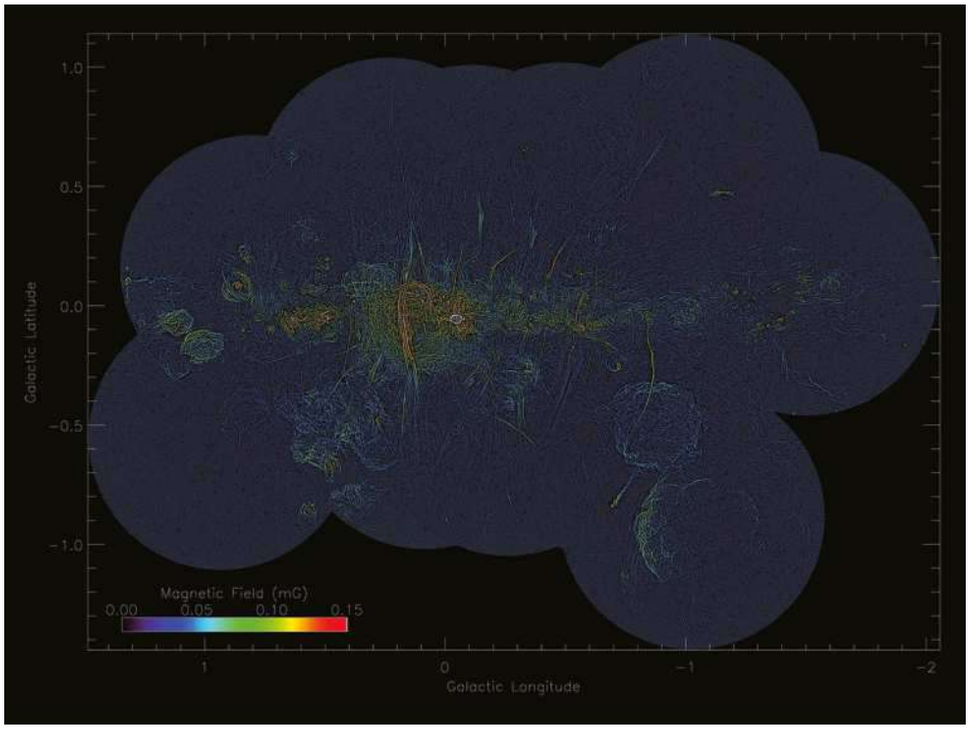
Step forward the South African Radio Astronomy Observatory's MeerKAT radio telescope, which was inaugurated in 2018. Located in the Northern Cape



of South Africa, it consists of 64 antennae spread across a diameter of eight kilometres (five miles). Each dish is 13.5 metres (44 feet) in diameter, and together they make up the most sensitive radio telescope on Earth – just the thing needed to go some way towards clearing up a mystery such as this. "The telescope is a big leap forward," Yusef-Zadeh affirms. "It's new and it has a broad band. It's located in the Southern Hemisphere and it is geographically advantageous to observe the galactic centre for 12 hours a day. In addition, more than 200 hours were spent observing a big region of the sky and three years of processing. The level of dedication, the location and the strategy were different from previous surveys." It has certainly made a massive difference to his study.

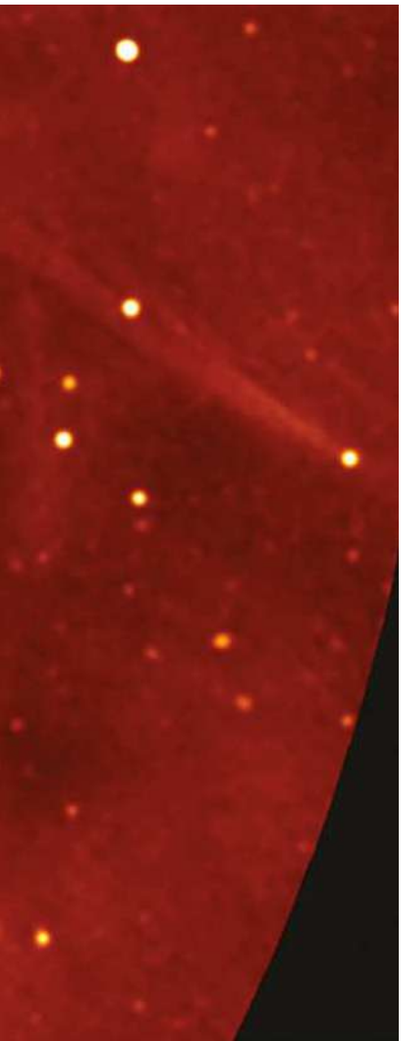
Those 200 hours have enabled astronomers to produce a mammoth mosaic of 20 separate observations at radio wavelength covering an area of the sky about 30 times the area of the full Moon. They have given researchers a very clear picture towards the centre of our galaxy, 25,000 light years away, and not only are the filaments clearly shown, it's now evident there are far more than were previously known about.

In fact, the 100-megapixel image is so clear and detailed thanks to MeerKAT's ability to pick up on synchrotron radiation created by the flow



© Northwestern University/SAORO/Oxford University

"THE FILAMENTS WERE MAINLY DIRECTED PERPENDICULAR TO THE GALACTIC PLANE" FARHAD YUSEF-ZADEH



© SARAO

Above: With the background removed, this mosaic image allows you to more clearly see the magnetic filaments

Left: A rare spherical supernova remnant found during studies of the filaments

along the length of the strands that it's possible to identify ten times more filaments than previously discovered. That's 1,000 of these mysterious strands, collectively offering a far greater chance of understanding these structures than ever before. "We can see a population of filaments and learn about the statistical properties of them. It's a feat that has not been previously possible," Yusef-Zadeh says.

To obtain the best possible look at the filaments, the astronomers removed the background from the main image. This isolated the filaments from their surrounding structures, and it's made some very clear patterns plain to see. For example, the filaments that were discovered decades ago were found in pairs and clusters, and nothing in the new data suggests any departure from that. Instead the image is so clear, the filaments are very noticeably stacked and equally spaced, in a manner described by the researchers as being like strings on a harp. "We are learning about spacing between filaments and looking to explain the origin of filamentation with pronounced spacing in the context of an instability in the interstellar medium of the galactic centre," Yusef-Zadeh says.

The filaments also possess a magnetic field that is much higher than expected from the galaxy – something noted in the study published in *The Astrophysical Journal Letters*. "By studying the magnetic fields you learn about the energetics, the spectrum of cosmic-ray particles and the strength of the magnetic field," he continues. "All of these are related to physical properties of the filaments so that a theoretical model can explain these properties. The goal is to understand processes that can accelerate particles to relativistic energies."

There are some clues. Yusef-Zadeh has previously found that radio waves are generated from the filaments when high-energy cosmic-ray particles collide with the filaments' magnetic fields and gyrate at close to the speed of light. But the problem here is that no one knows where those high-energy cosmic-ray particles are coming from. There was a chance that the source could have been shared by a recently discovered supernovae, but more detailed studies have ruled this out – it appears that the wavelengths of light emitted by the filaments are varying to a greater degree than the wavelengths coming from the remnants of the supernova, pointing towards a different origin.

If anything, the researchers say, the filaments are more likely to be related to the past outburst activity of our galaxy's central supermassive black hole, Sagittarius A*. Intriguingly, they may also be related to giant radio-emitted bubbles hundreds of light years tall which were found dwarfing other

> "LENGTH DISTRIBUTION IS NEXT ON THE LIST OF MYSTERIES THAT WE WANT TO RESOLVE IN RELATION TO THE FILAMENTS" FARHAD YUSEF-ZADEH

structures at the centre of the Milky Way in 2019 by, among others, Yusef-Zadeh. "It's complicated to explain, but mainly this idea requires a large-scale wind – one that's likely produced by high cosmic ray pressure in the galactic centre," he explains. "In this theory, this wind is also producing the bubble."

According to the paper, which is also authored by Oxford University astrophysicist Ian Heywood, the triggering event would be enhanced accretion onto the black hole or a burst of star formation several million years ago. Our black hole has a tendency to become uncharacteristically active.

Still, such a theory is far from being confirmed, and more studies are needed. The researchers also say they want to discover why the filaments are so well structured and separated. "If you look at a large number of filaments statistically, those that lie next to each other have an ordered spacing between them of about 0.5 parsecs," Yusef-Zadeh says of a distance about equal to that between the Sun and Earth. In that sense it would appear that the mysteries just keep stacking up, ensuring the filaments are sure to be studied for many more years to come.

In fact, researchers say that they're keen to discover whether or not the filaments move or change over time. They also want to know what causes the electrons to accelerate at great speeds. "Then there's the length distribution, which is next on the list of mysteries that we want to resolve in relation to the filaments," Yusef-Zadeh tells **All About Space**. "We want to know why some filaments are longer and some are shorter; we want to know what the distribution is and we want to discover how they are related to the strength of the magnetic field and to the spectrum of cosmic-ray particles."

For now work continues in cataloguing and observing the filaments so that the researchers have a database logging the magnetic field, spectrum, curve, angle and intensity of each one of them. The more the astronomers can find out about the filaments, the greater the chance they have of working out just where they came from. In

TAKING A SNAPSHOT OF THE GALACTIC CENTRE

This stunning image taken by MeerKAT gives us a detailed look at the Milky Way's central region

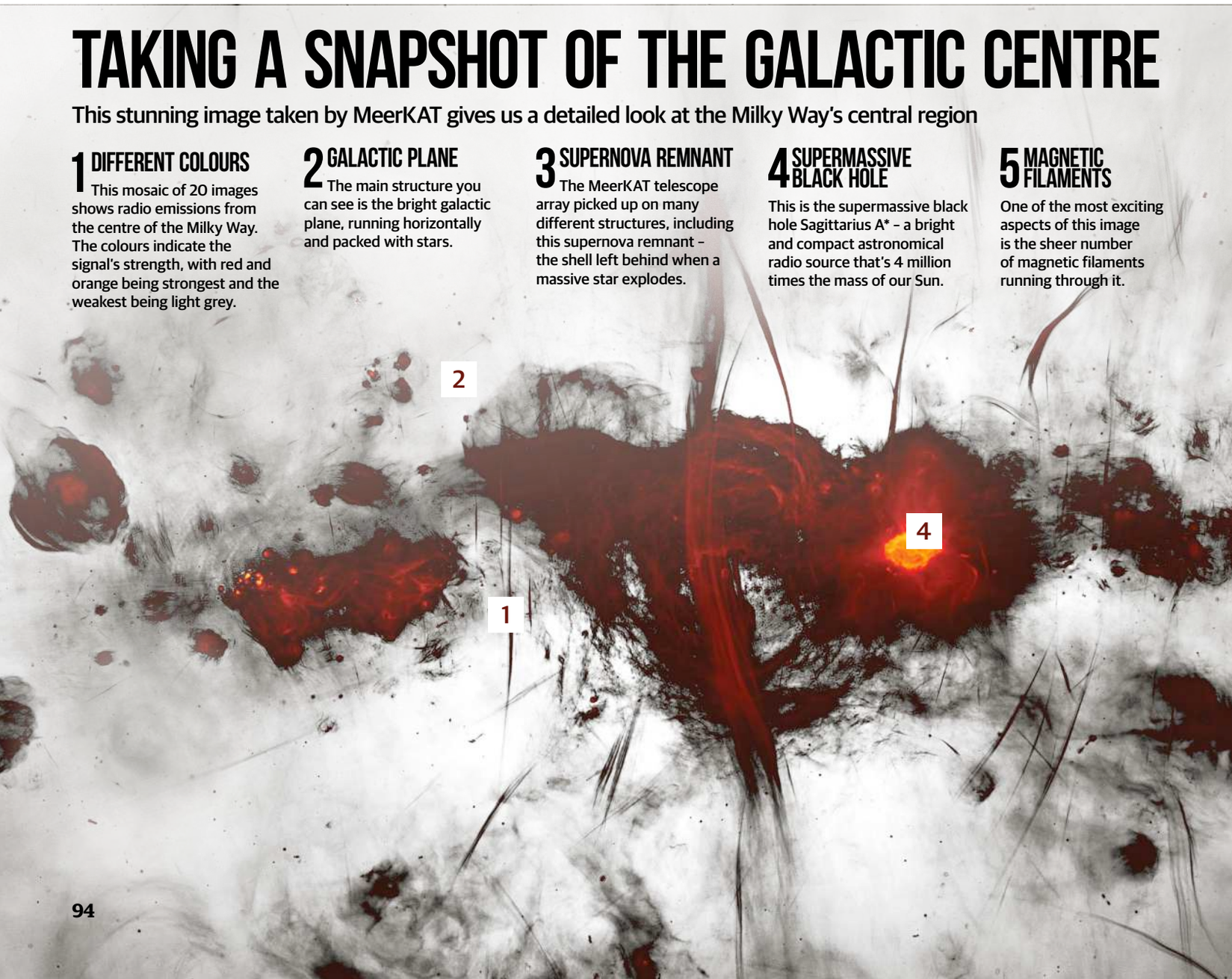
1 DIFFERENT COLOURS
This mosaic of 20 images shows radio emissions from the centre of the Milky Way. The colours indicate the signal's strength, with red and orange being strongest and the weakest being light grey.

2 GALACTIC PLANE
The main structure you can see is the bright galactic plane, running horizontally and packed with stars.

3 SUPERNOVA REMNANT
The MeerKAT telescope array picked up on many different structures, including this supernova remnant – the shell left behind when a massive star explodes.

4 SUPERMASSIVE BLACK HOLE
This is the supermassive black hole Sagittarius A* – a bright and compact astronomical radio source that's 4 million times the mass of our Sun.

5 MAGNETIC FILAMENTS
One of the most exciting aspects of this image is the sheer number of magnetic filaments running through it.

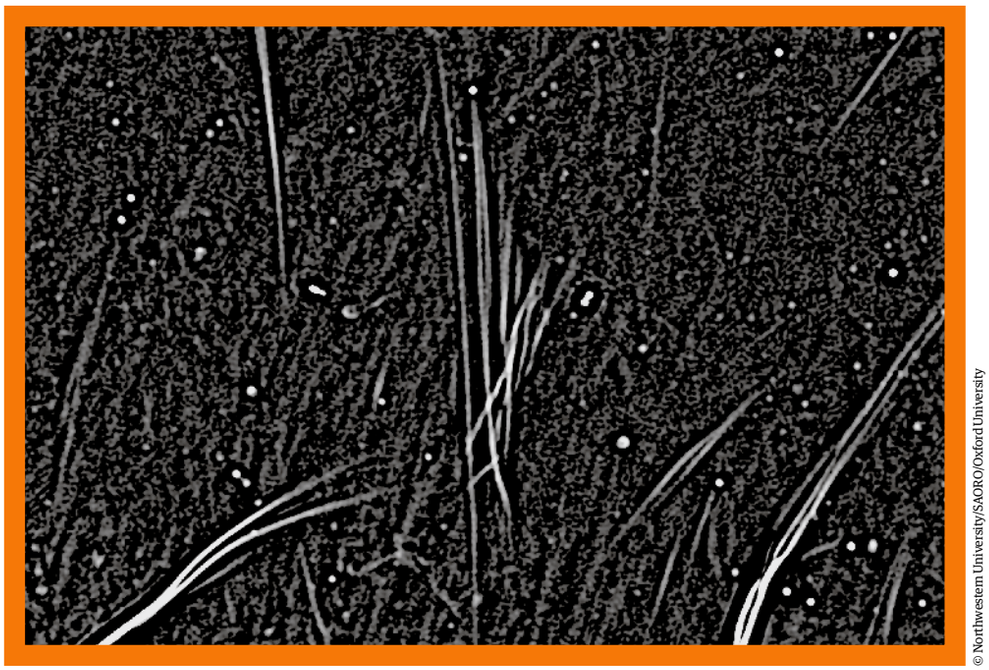


that sense they are far closer than ever before. It may have taken 35 years, but as Yusef-Zadeh says, these things take time.

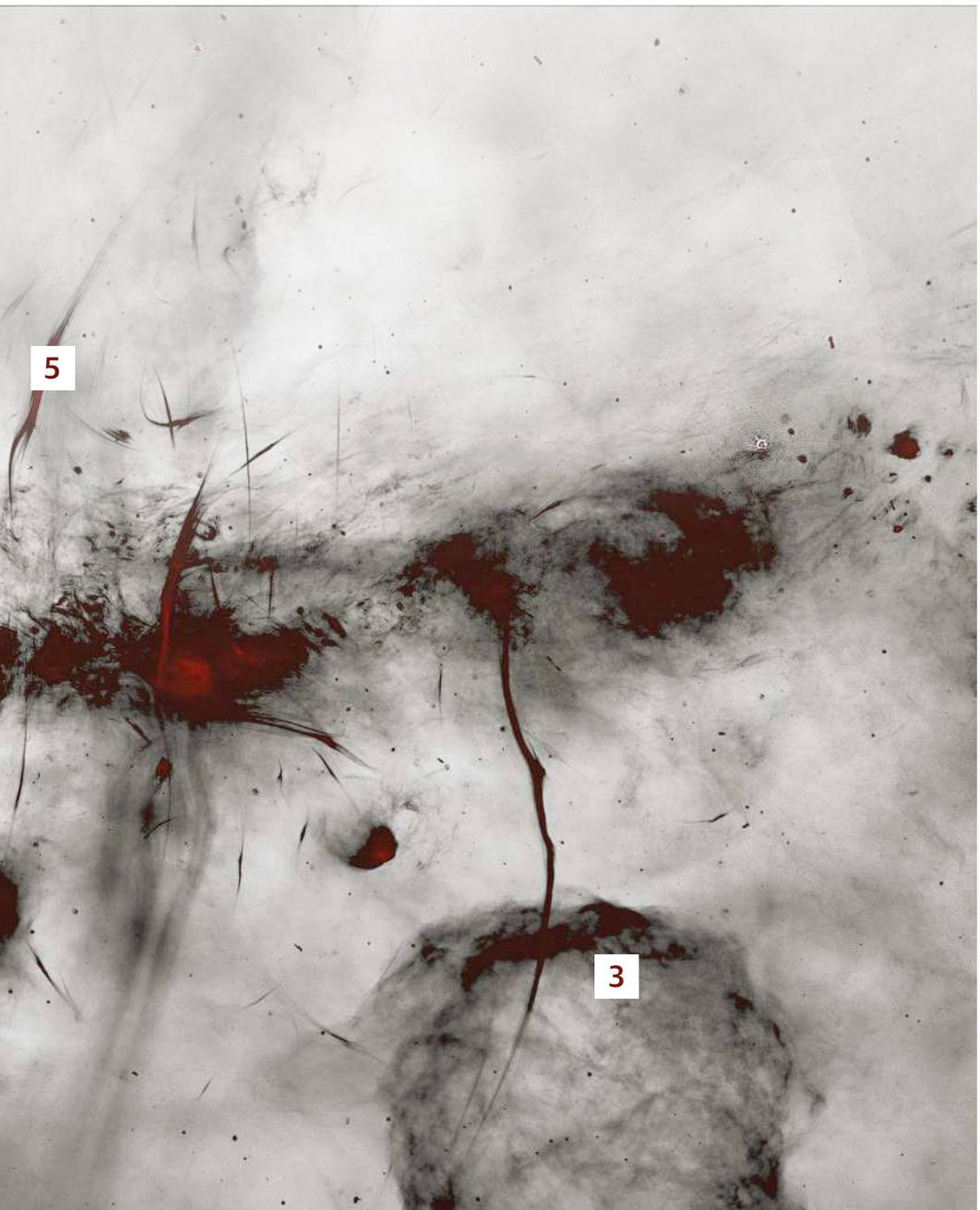
And that's not all. The image generated using data from MeerKAT has also thrown up other phenomena. As well as new supernova remnants, the clear imagery shows outbursting stars, stellar nurseries and other compact radio wave sources that likely show supermassive black holes outside of our galaxy. It's a mosaic that's sure to be pored over by many different teams for a long time to come. Both this and MeerKAT have the potential to clear up other great mysteries, and it'll be exciting to see what comes next.



David Crookes
Science and technology journalist
David has been reporting on space, science and technology for many years, has contributed to many books and is a producer for BBC Radio 5 Live.



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© J. Heywood/Sarao

Above: The magnetic filaments in this image look broken

WHERE DID THE MAGNETIC FILAMENTS ORIGINATE?

We know they exist, but their origin remains a mystery

BURSTS OF SUPERNOVAE

There's a possibility that the filaments are due to coordinated outbursts of energy from supernova explosions, but astronomers say this is very unlikely. Radiation emitted from the filaments has different variations from supernova remnants, so the origins are likely different too.

PAST BLACK HOLE ACTIVITY

It's more likely the filaments are related to our supermassive black hole, Sagittarius A*. The team are tracking energetic sources of cosmic-ray particles radiating in the radio band. Time stamping matches the particles to a period of black hole outburst.

BUBBLES OF GAS

There are two enormous radio-emitting bubbles, shaped like an hourglass, inflating from a black hole outburst which may have occurred up to a million years ago. Discovered by MeerKAT in 2018, the radio bubbles may have interacted with star formation to create the filaments.



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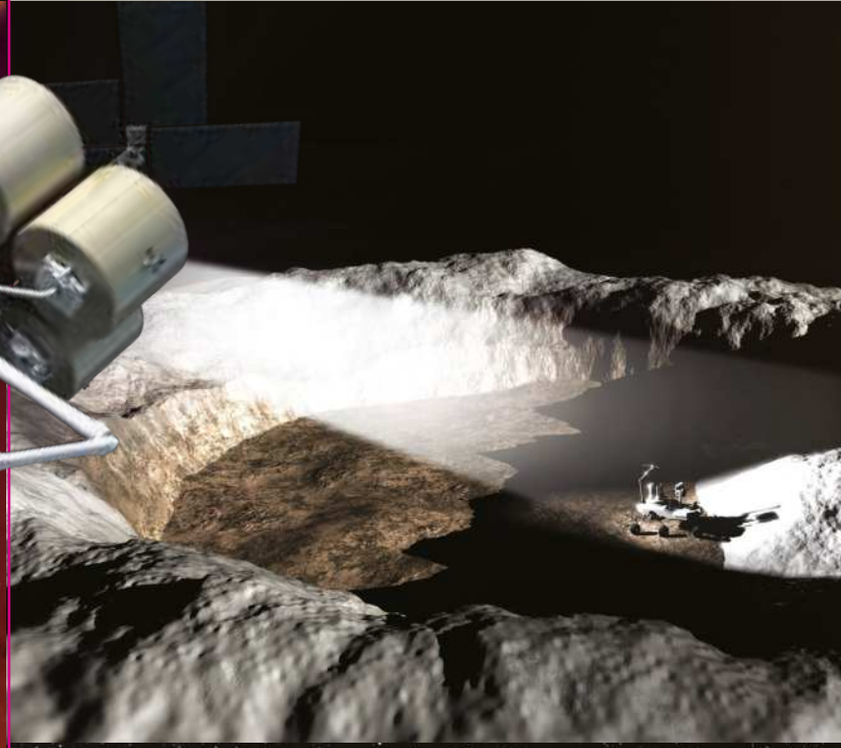
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10 SPACE INNOVATIONS

GROUNDBREAKING TECHNOLOGIES THAT WILL REVOLUTIONISE HOW WE EXPLORE THE COSMOS

Reported by Jonathan O'Callaghan

As our ambitions for exploring space become greater, so too do our technological needs. Our current technologies and methods place limits on what we can do, limits that we are starting to press upon as more daring and exciting missions are devised.

To fulfil our grander ambitions, a variety of companies and agencies are carrying out the research and development that will provide the new technologies we need – from advanced propulsion techniques to reusable rockets.

With that in mind, we've chosen ten technologies that we think could revolutionise our methods of exploring and understanding the universe around us. Some are proposals we'd expect to see in the next few years; others are wholly more ambitious concepts. Join us as we unveil the incredible future space technologies that will change our methods of space exploration and observation forever.

1 Environment transformers

On the Moon, Mars, Mercury and potentially other worlds within our galaxy, we know of permanently shadowed craters and caves that receive no sunlight. These areas are of particular interest to scientists as they may contain significant quantities of ice that could be studied. However, the problem with ice is that it's pretty solid. Unless you've got a human explorer or a rover with a drill, it's difficult to do anything with it. That's where transformers come in. These multifunctional platforms would be placed at the rim of a crater, where they would then reflect incoming sunlight, using mirrors, onto specific sections of the ice. This would melt it, allowing an automated rover to analyse the resultant water.

This incredible technology could provide us with a low-cost option for accessing ice and water across the Solar System, giving us clues into planetary formation and perhaps even supplying future astronauts with a resource of water.

1 SUNLIGHT
Some craters that we know of are permanently shadowed, receiving no sunlight and enabling ice to remain present.

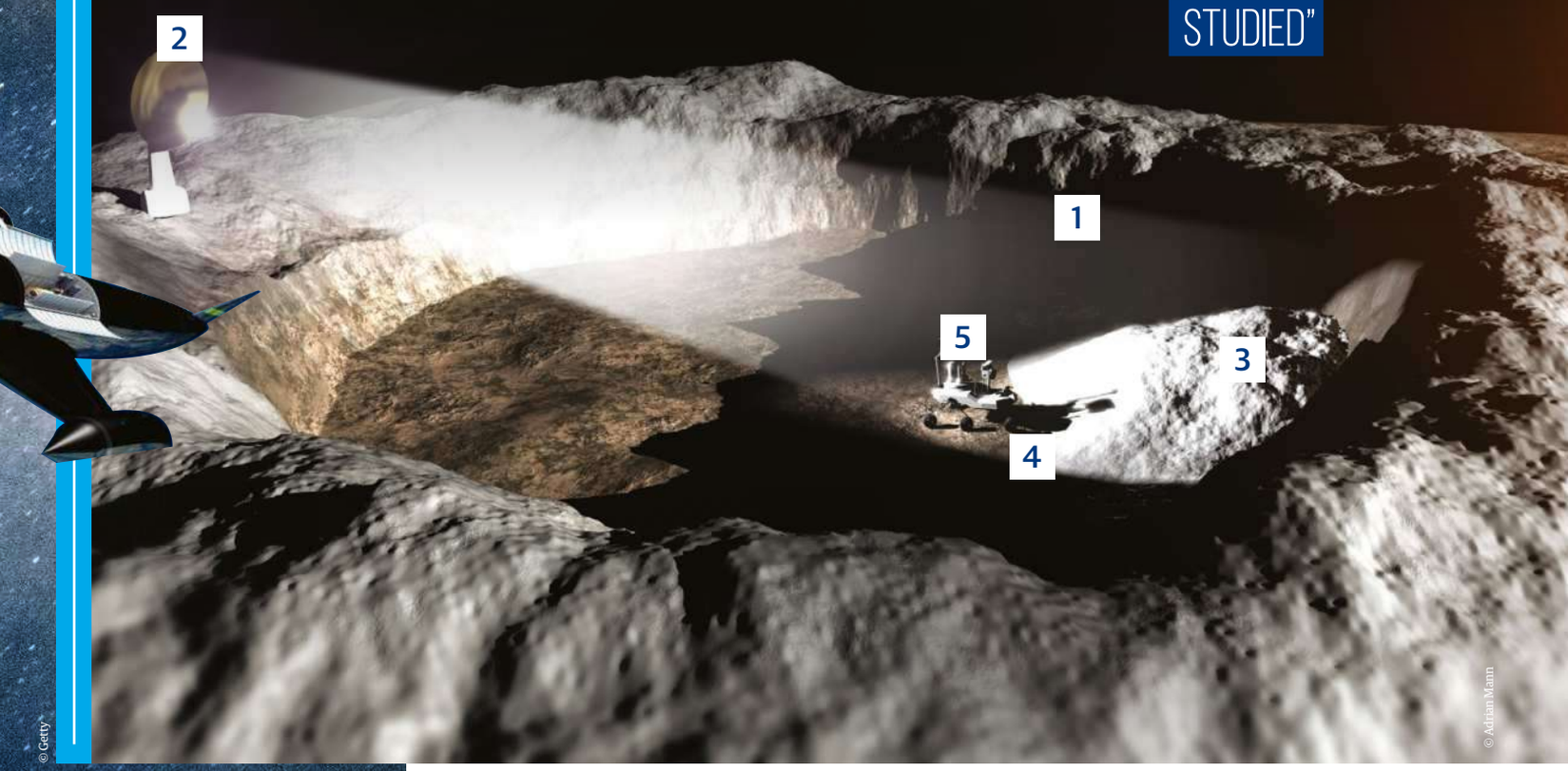
2 TRANSFORMER
A transformer would be placed at the rim of a crater, reflecting incoming sunlight onto some of the ice.

3 ICE
Ice found on worlds such as Mercury and Mars could contain secrets into the planets' history and formation.

4 ROVER
An automated rover placed on the ice would analyse the areas melted by the transformer, getting access to liquid water.

5 POWER
An added bonus of this proposal is that the reflected sunlight could help power solar panels on the rover.

"THESE AREAS ARE OF PARTICULAR INTEREST TO SCIENTISTS AS THEY MAY CONTAIN SIGNIFICANT QUANTITIES OF ICE THAT COULD BE STUDIED"



© Getty
© Adrian Mann



© NASA

2 Inflatable space stations

Could we send compact space stations up into orbit, having them then unfold in space by pumping gas into them? Bigelow Aerospace thinks so, and it's hard at work on such technology. Bigelow has actually already tried and tested this idea with its Genesis I and II modules in 2006 and 2007 respectively. The company then successfully connected an inflatable habitat to the ISS in 2016. The ultimate step will be to launch a standalone module, called the B330, that can inflate and operate by itself in orbit, forming the world's first inflatable station to be used for scientific endeavours, but also as a 'hotel' of sorts for tourists to visit.

3 Tiny robots on Titan



Landing on other worlds has always been a struggle. You have to contend with gravity and possibly an atmosphere as you make your way to the surface, often employing complex and sophisticated landing mechanisms that are not only costly, but also risky. Apparently, though, when a team at NASA made a tensegrity structure like the one below, they accidentally dropped it on the floor and it survived, intact. They wondered if the same sort of structure could be dropped onto the surface of another world without needing to use parachutes or rockets to lower it to the surface. The answer is probably yes.

Small and low-cost missions are going to be increasingly important as we move forward in our space exploration endeavours. This particular idea involves using tensegrity structures – ones with interlocking tubes that create a net tension across the entire structure – to land on another world such as Titan without the need for an additional landing mechanism. By being dropped from a spacecraft in orbit or flying past Titan, the structures could be left to fall through the atmosphere and land on the ground, ready to perform experiments with no mission-ending damage.

Tens or perhaps even hundreds of these small machines could be packed into a spacecraft for distribution at Titan. Each could contain different experiments, ranging from cameras to environmental sensors, while the machines would also be collapsible, allowing them to get direct analysis of the ground.

It's an ambitious proposal, but it's one that seems to be entirely possible. And it's not just Titan these could be used on – the high-impact absorption of these robots means they could also be employed pretty much anywhere in the Solar System.

1 DROP
Perhaps hundreds of these tiny robots could be dropped from a spacecraft in orbit around Titan, making their way to the surface with no landing mechanism.

2 IMPACT
The tensegrity structure allows the robots to withstand the high-impact forces they will experience when they make contact with the ground.

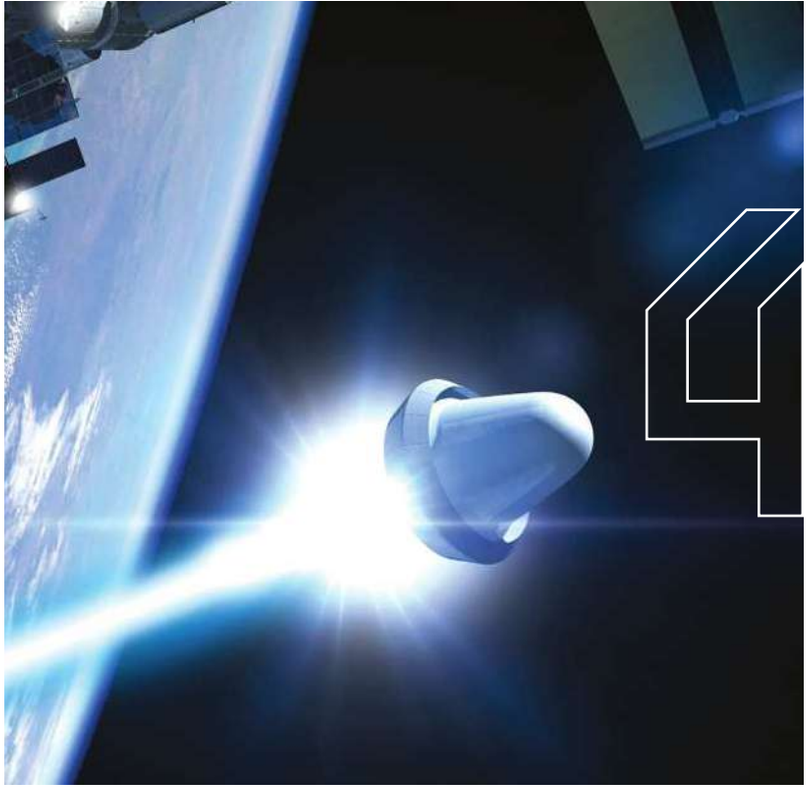
3 COLLAPSE
The robots can collapse to help them withstand the force of landing, transferring the energy of the impact away and resulting in the robots bouncing on the surface.

4 EXPERIMENTS
Within each tube the robots could contain a number of experiments to study the surface of Titan, including environmental sensors and cameras.

5 OPERATION
The robots would be able to perform extensive scientific analysis, such as collapsing to study the ground, while transmitting their findings to a spacecraft in orbit for relay.



© Adrian Mann



© Adrian Mann

Laser thrusters

One of the biggest limits upon our exploration of the Solar System is fuel. To traverse large distances you either need a lot of fuel, or a clever path that incorporates the gravitational pull of the planets. Carrying large amounts of fuel comes at a cost, and not just a financial one – it also restricts how much useful payload you can take, such as scientific instruments.

It has long been desirable to build a spacecraft that can be pushed by a new form of propulsion that breaks the limits of what is currently possible. One such solution might be a recent NASA proposal that suggests we could build propellantless spacecraft pushed along by photons – light particles – or lasers.

The technology is very much in its infancy, but it's very intriguing nonetheless. One concept could see a solar array in Earth orbit direct photons onto a spacecraft. A 100kW solar panel would produce up to one Newton of constant photon thrust on a spacecraft, accelerating it to high speeds.

"IT WOULD ALLOW US TO BUILD STRUCTURES IN SPACE AS OPPOSED TO LAUNCHING THEM FULLY COMPLETE FROM EARTH"

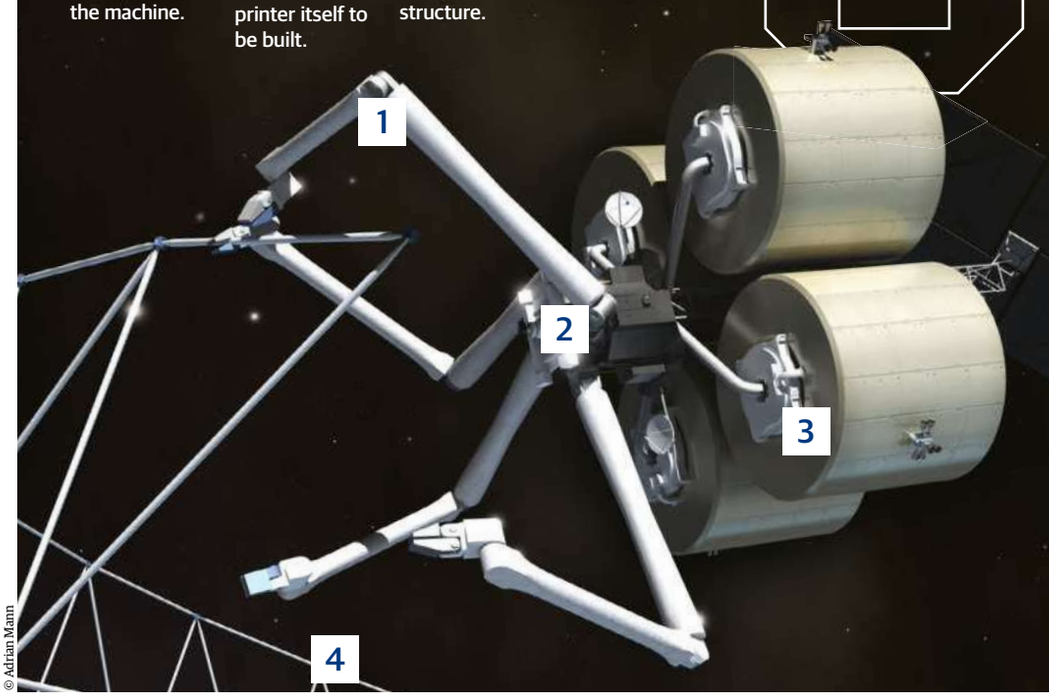
In-orbit assembly

1 COMPACT The use of SpiderFab would enable structures to be launched compactly before being built in orbit by the machine.

2 3D PRINTING SpiderFab will use an inside-out 3D printer, allowing structures much larger than the printer itself to be built.

3 SPOOLS Material is held in spools on SpiderFab before being 'spun' by its arms into the required shape of the structure.

4 STRUCTURES The structures that could be built by SpiderFab include large antenna reflectors and solar arrays.

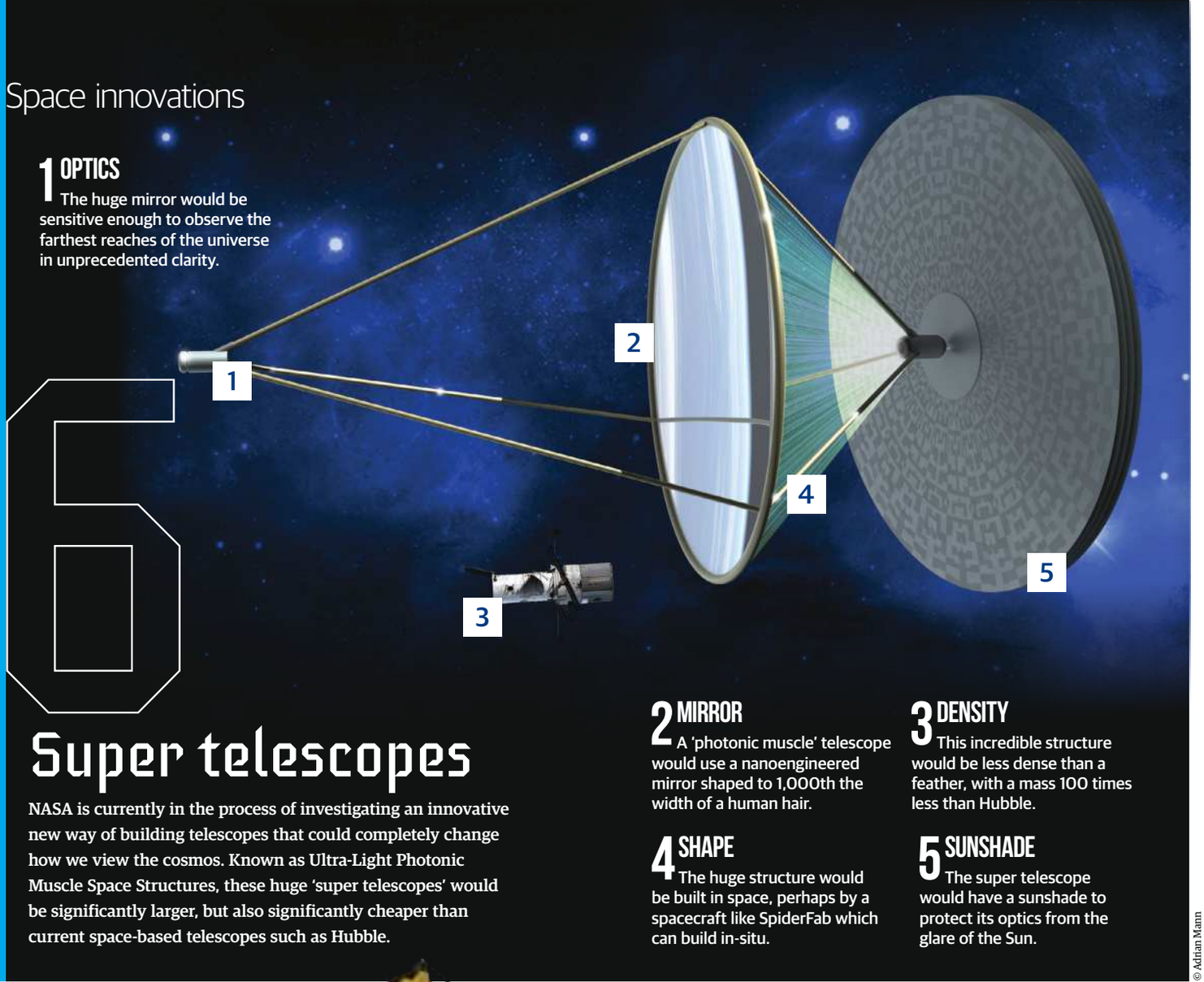


© Adrian Mann

To become a true spacefaring civilisation we will need to learn how to construct spacecraft in space rather than launching them from Earth. With that in mind, aerospace company Tethers Unlimited has proposed a new technology called SpiderFab that will be able to build structures in orbit from materials fed into the machine. SpiderFab would be launched into orbit by a rocket, and once there would use spools of material – most likely carbon fibre – to assemble huge structures.

The material is fed from spools to a 3D printer, turning it into a 'web' of sorts that the arms can then contort into the required structure. This could be a variety of things, including a support structure for a solar array or the backbone of a telescope. If successful, this technology would be revolutionary; it would allow us to build structures in space as opposed to launching them fully complete from Earth.

With the necessary funding, SpiderFab could be ready for a small demonstration within a few years. A prototype, the 'Trusselator', which will use spools of carbon fibre to make high-performance composite trusses is being prepared.



1 OPTICS
The huge mirror would be sensitive enough to observe the farthest reaches of the universe in unprecedented clarity.

2 MIRROR
A 'photonic muscle' telescope would use a nanoengineered mirror shaped to 1,000th the width of a human hair.

3 DENSITY
This incredible structure would be less dense than a feather, with a mass 100 times less than Hubble.

4 SHAPE
The huge structure would be built in space, perhaps by a spacecraft like SpiderFab which can build in-situ.

5 SUNSHADE
The super telescope would have a sunshade to protect its optics from the glare of the Sun.

© Adrian Mann

6 Super telescopes

NASA is currently in the process of investigating an innovative new way of building telescopes that could completely change how we view the cosmos. Known as Ultra-Light Photonic Muscle Space Structures, these huge 'super telescopes' would be significantly larger, but also significantly cheaper than current space-based telescopes such as Hubble.

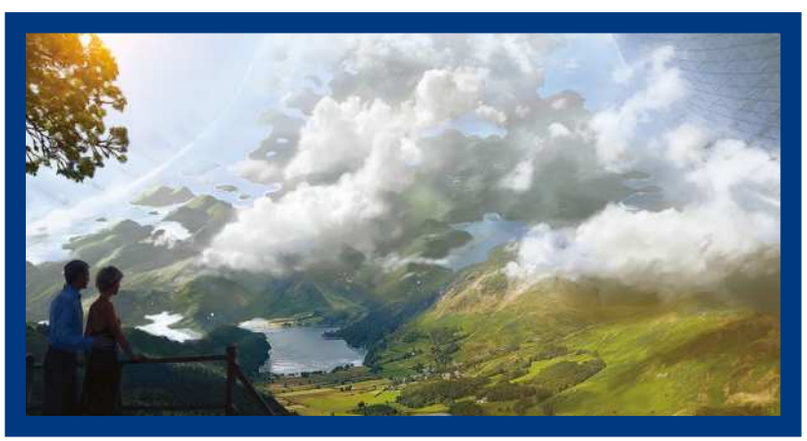


7 Observing exoplanets

In November this year, NASA's James Webb Space Telescope (JWST) will launch, the most powerful space telescope humanity has ever built. While it will offer unrivalled views of the cosmos, some scientists have suggested that there are additional features we could use with the JWST to revolutionise the field of astronomy.

One of those is to launch a starshade with the telescope. The technology has been around for years, but budget restraints have seen it remain a concept rather than an actual mission. A giant shade would be used to block the light of a distant star known to harbour exoplanets, and a powerful telescope, such as the JWST, would peer just past the shade and be able to directly observe the exoplanets. Such a proposal for a starshade-centric telescope is currently under consideration by NASA for funding. If picked, it could offer a whole new insight into exoplanets.

© Adrian Mann

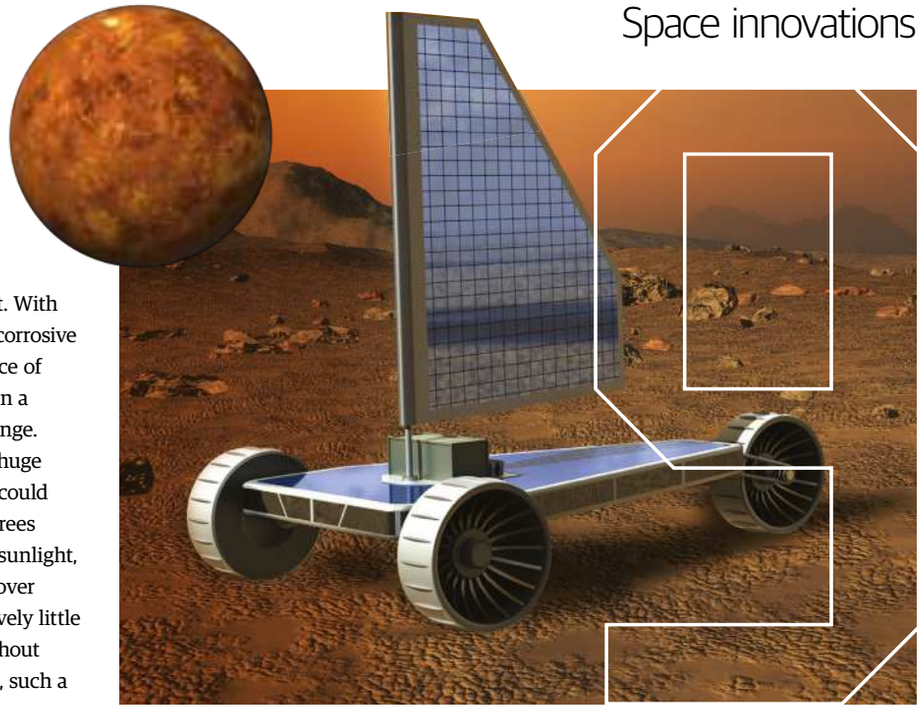


© Peter Rubin

8 Space habitats

A recent concept proposal to NASA has suggested that the tensegrity structures we discussed for use on Titan could also be used to build a space habitat near the Moon, albeit on a far larger scale. The lightweight structure would use water gleaned from space-based materials as a means to provide shielding for its inhabitants. Known as Growth-Adapted Tensegrity Structures, these could be an excellent way to build large-scale habitats in space.

Windsailing on Venus



© Adrian Mann

One of the most hostile places in the entire Solar System, the surface of Venus is also incredibly intriguing thanks to its fascinating climate, bizarre history and turbulent present. With a surface temperature hot enough to melt spacecraft and a corrosive atmosphere, so much so that our only missions to the surface of Venus, the Soviet Venera probes, could survive no more than a couple of hours on the surface, landing there is a real challenge.

Landing a rover on the surface of Venus would require a huge engineering marvel. The rover would need electronics that could survive temperatures of up to 450 degrees Celsius (842 degrees Fahrenheit) in addition to solar cells that could get enough sunlight, even with the thick Venusian atmosphere. A sail-powered rover would enable a vehicle to operate on the surface with relatively little amounts of energy; it could drift on the winds of Venus without needing to drive itself much. According to a NASA proposal, such a mission is not too far off being possible.

10

The SABRE engine

One of the problems with building a true spaceplane is that an engine needs to operate within the atmosphere of Earth and the vacuum of space. Reaction Engines is currently hard at work on its futuristic spaceplane known as Skylon, which will employ a revolutionary engine known as SABRE that enables the operation of the vehicle in both environments. While taking off from the ground the engine remains in air-breathing mode, drawing in oxygen like a jet engine. When above the atmosphere it enters rocket mode, using onboard liquid oxygen to reach orbital speeds. Components of the engine have already been tested, and it could be one of the most significant advancements in spaceplane technology yet.

© Reaction Engines Ltd

ARE WE CLOSER TO REVEALING THE SECRETS OF PLANET FORMATION?

Data gathered by a host of radio dishes perched high in the Chilean desert teases apart the mysteries of how worlds form

Reported by Meghan Bartels

The Atacama Large Millimeter/submillimeter Array (ALMA) specialises in studying protoplanetary discs, the mess of material that surrounds young stars and eventually comes together to build planets. While scientists do plenty of work analysing already-formed exoplanets, studying protoplanetary discs offers an opportunity to see all those ingredients mixed up and spread out.

A new set of 20 papers shares results from a research program called Molecules with ALMA at Planet-forming Scales (MAPS), which uses the powerful facility to study protoplanetary discs. One of the new papers maps the presence of more than a dozen organic molecules throughout five different protoplanetary discs. Organic molecules, which contain carbon, are of particular interest to scientists trying to understand how life begins.

"These planet-forming discs are teeming with organic molecules, some of which are implicated in the origins of life here on Earth," Karin Öberg, an astronomer at the Harvard-Smithsonian Center for Astrophysics (CfA) and principal investigator for MAPS, said. "This is really exciting. The chemicals in each disc will ultimately affect the type of planets that form, and determine whether or not the planets can host life."

The maps don't only show that organic compounds exist in protoplanetary discs; they show that the distribution of such ingredients varies. That means two planets forming in different regions of the same protoplanetary disc could end up with vastly different supplies of these compounds. "Our maps reveal it matters a great deal where in a disc a planet forms," Öberg said. "Two planets can form around the same star and have very different organic inventories, and therefore predispositions to life."

In addition to locating different ingredients, the research also identified compounds built with deuterium, which is a form of hydrogen

Main: New findings highlight the distribution of matter before planets form

© Getty



twice as heavy as the most commonly found flavour of the element. The research suggested that deuterium levels vary across a disc, with much less of the atom found closer to the star at the heart of the disc.

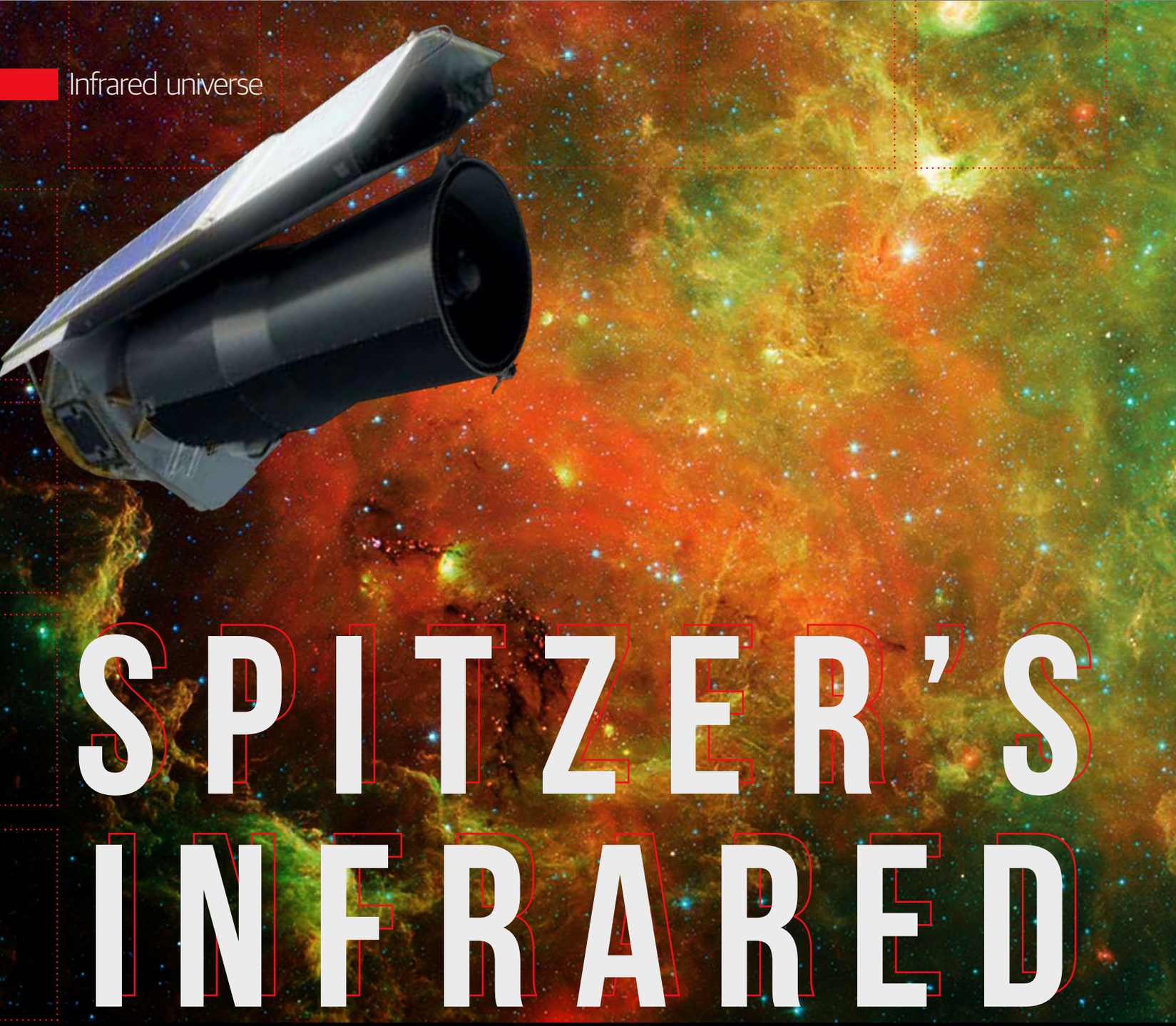
Scientists were also able to detect the very earliest signs of a planet coalescing out of a disc. That's usually very difficult - the same dust and debris that forms the disc itself also blocks the tiny baby stages of planets. "It's like trying to see a fish underwater," said Richard Teague, lead of a segment of the MAPS project. "We know they're there, but we can't peer that far down. We have to look for subtle signs on the surface of the water, like ripples and waves."

Another segment of the MAPS research focused on the precursors of massive Jupiter-like planets, in which elements like carbon and oxygen seemed to be much rarer than compounds like methane. "Our findings suggest that many gas giants may form with extremely oxygen-poor (carbon-rich) atmospheres, challenging current expectations of planet compositions," Arthur Bosman, an astronomer at the University of Michigan and lead author of one of the papers, said.

"THESE PLANET-FORMING DISCS ARE TEEMING WITH ORGANIC MOLECULES, SOME OF WHICH ARE IMPLICATED IN THE ORIGINS OF LIFE" KARIN ÖBERG

The new research shows that there's plenty more to learn about what surrounds young stars, how planets form and what that means for the universe and life's prospects in it.

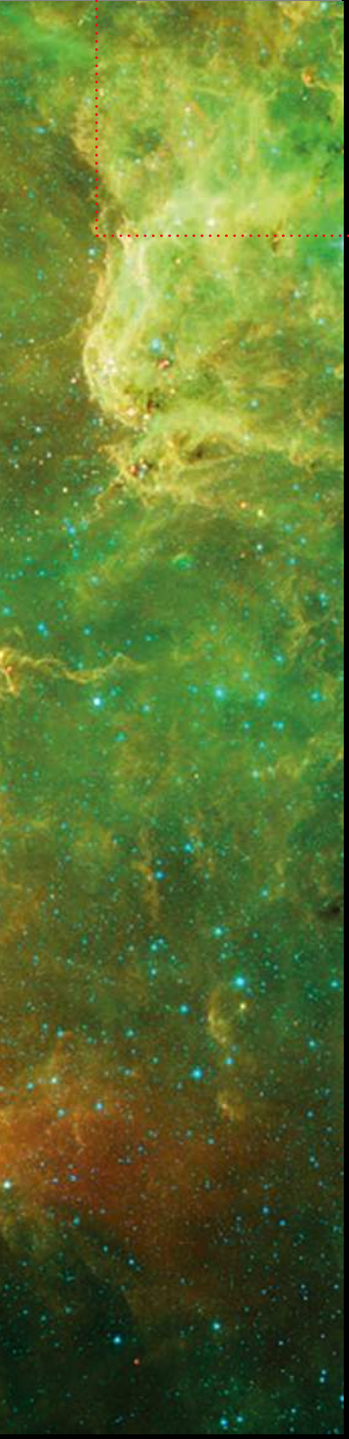
"We're hoping to use ALMA to search for the next stepping stones of chemical complexity in these discs," said John Ilee, an astronomer at the University of Leeds and lead researcher on a new MAPS study. "If we detect them, then we'll be even closer to understanding how the raw ingredients of life can be assembled around other stars."



SPITZER'S INFRARED UNIVERSE

IN JANUARY 2020, NASA'S SPITZER SPACE TELESCOPE CAME TO THE END OF ITS MISSION AFTER 16 YEARS OF INCREDIBLE IMAGES – HERE'S JUST A FEW OF OUR FAVOURITES

Written by Hanneke Weitering



CARINA NEBULA

Massive stars can wreak havoc on their surroundings, as can be seen in this view of the Carina Nebula. The bright star at the centre of the nebula is Eta Carinae, one of the most massive stars in the galaxy. Its blinding glare is sculpting and destroying the surrounding nebula.

NORTH AMERICA NEBULA

Spitzer captured this infrared view in 2011. Since infrared light can penetrate dust, the shape of the nebula – which usually resembles the continent of North America – changes completely. The dusty, dark clouds in visible-light images vanish in Spitzer's view. In addition, Spitzer's infrared detectors display the glow of dusty cocoons enveloping baby stars.

THE SWAN NEBULA

Spitzer captured this infrared view of the choppy star-making cloud Messier 17, also known as the Omega Nebula or the Swan Nebula, in 2008. The region lies around 5,500 light years away in Sagittarius.





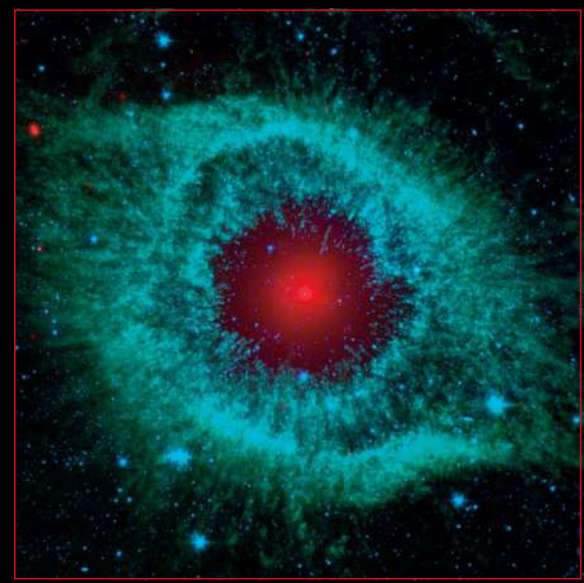


DUMBBELL NEBULA

The Dumbbell Nebula, also known as Messier 27, pumps out infrared light in this image. The nebula was named after its resemblance to a dumbbell as seen in visible light. It was discovered in 1764 by Charles Messier, who included it in his famous catalogue of nebulous objects.

PENGUIN AND EGG GALAXIES

The galaxies NGC 2336 and NGC 2937 look like a penguin and its egg respectively in this photo, which incorporates data from NASA's Hubble and Spitzer space telescopes.



HELIX NEBULA

This infrared image from Spitzer in 2007 shows the Helix Nebula, a cosmic starlet often photographed by amateur astronomers for its vivid colours and eerie resemblance to a giant eye in the sky.

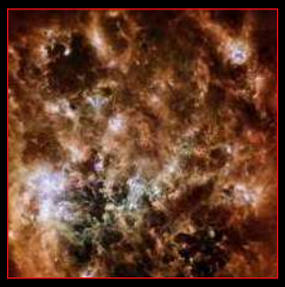


All images © NASA/JPL-Caltech



GREEN RING NEBULA

A glowing ring spotted in space seems more like superhero fiction than science fact. But that's what Spitzer found in the murky clouds encircled by the tail of Scorpius. This photo of the bright emerald-green nebula, released in 2011, is reminiscent of the glowing ring wielded by the Green Lantern.





A DUSTY MAGELLANIC CLOUD

This image shows the Large Magellanic Cloud in infrared light as seen by Spitzer and the European Space Agency's Herschel Space Observatory. In this combined image, the dwarf galaxy looks like a fiery, circular explosion. Those ribbons are actually giant ripples of dust.

"THIS PHOTO OF THE BRIGHT EMERALD-GREEN NEBULA IS REMINISCENT OF THE GLOWING RING WIELDED BY THE GREEN LANTERN"

SPIRAL GALAXY SPIDER WEB

Looking like a spider's web swirled into a spiral, the galaxy IC 342 presents its delicate pattern of dust in this image, captured by Spitzer in 2011. Seen in infrared light, the faint starlight gives way to the glowing patterns of dust found throughout the galaxy's disc.

GALAXY BLASTED WITH A DEADLY JET

Spitzer captured a powerful jet from a supermassive black hole blasting a nearby galaxy in the system known as 3C 321. This galactic violence could have a profound effect on any planets in the path of the jet and trigger a burst of star formation.







BLACK HOLE IN A COSMIC STORM

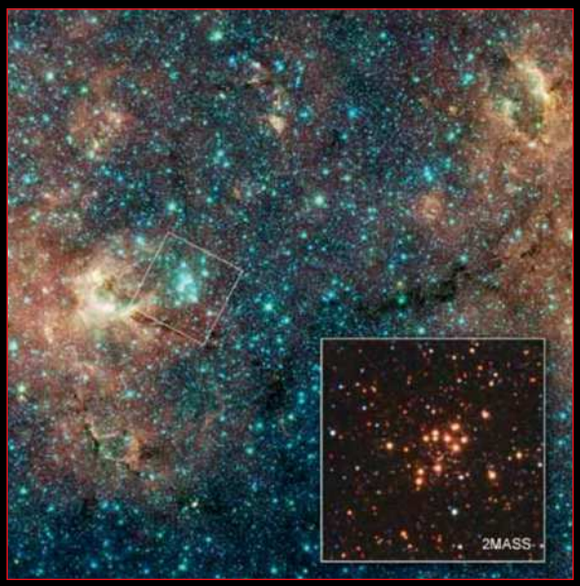
The 'eye' at the centre of the barred spiral galaxy NGC 1097 is caused by a monstrous black hole. It can't be seen, but is surrounded by a ring of stars and rampant star birth. In this colour-coded infrared view from Spitzer, the area around the invisible black hole is blue and the ring of stars is white.

SUPERNOVA REMNANT HBH 3

This supernova remnant is one of the largest in the Milky Way, measuring about 150 light years across. It's also one of the oldest; the star that exploded to create this cosmic spectacle did so 80,000 to 1 million years ago. Spitzer captured this image in May 2010, and NASA released it on 2 August 2018.

STELLAR FIREWORKS

Astronomers traced the source of mysterious high-energy X-rays and gamma rays in space to a little known star cluster in the Milky Way. This infrared image shows a region in the Scutum constellation where a massive star cluster containing red supergiants (inset) was discovered.



MOUNTAINS OF CREATION

Giant clouds of gas and dust harbouring embryonic stars rise majestically into space in this snap by Spitzer. The image, dubbed the Mountains of Creation by astronomers, reveals hotbeds of star formation similar to the iconic Pillars of Creation within the Eagle Nebula, photographed in 1995 by Hubble.

CYGNUS X STAR BIRTH

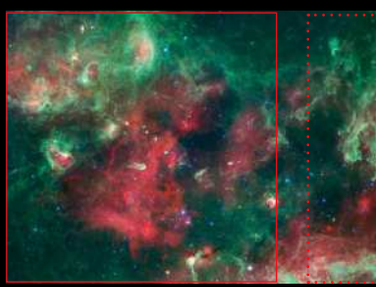
A bubbling cauldron of star birth, Cygnus X is highlighted in this 2012 image from the Spitzer Space Telescope. Infrared light - which we can't see with our eyes - has been colour-coded so that the shortest wavelengths are shown in blue and the longest in red. The middle wavelength range is green.

CASSIOPEIA A

Stars don't always rip apart in violent explosions. Some blow up in an orderly fashion. Cassiopeia A blew up in such a tidy manner that it retained much of its original layering. In this false-colour image, the blue glow is material heated by a forward shock wave, while green, yellow and red represent material heated by a reverse wave.







'HEART' OF THE MILKY WAY

In this image, observations using infrared and X-ray light see through the obscuring dust and reveal the intense activity near the galactic core of the Milky Way. The image combines data from Hubble, Spitzer and the Chandra X-ray Observatory.





THE SOMBRERO GALAXY

The infrared vision of Spitzer has revealed that Messier 104, or the Sombrero Galaxy - named after its appearance in visible light to a wide-brimmed hat - is in fact two galaxies in one. It's a large elliptical galaxy (red) with a thin disc galaxy (blue-green) embedded within.

All images © NASA/JPL-Caltech

RECORD-BREAKING VIEW OF THE MILKY WAY

This is just a section of the largest image of the Milky Way ever created. It was stitched together from 800,000 individual infrared images taken by NASA's Spitzer Space Telescope.





CEPHEUS STARS

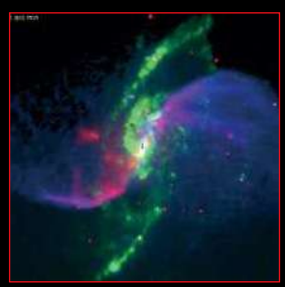
Because of its infrared sensitivity, Spitzer can get a stunning look at nebulae – clouds of dust and gas peppered across the universe. The puffy green structures are nebulae, with stars scattered within them, including Cepheus C on the left and one called Cepheus B in the upper-right corner.



A GALACTIC MYSTERY

Scientists using Spitzer discovered the source of a galaxy's two ghostly extra spiral arms, which only show up in some telescope images, cracking a mystery. Messier 106, a stately spiral galaxy 23.5 million light years away in Canes Venatici, appears in visible-light images to have just two prominent arms.







THE CAT'S PAW NEBULA

Spitzer captured this view of the Cat's Paw Nebula in 2018. The nebula, officially NGC 6334, gets its nickname from the bubbles of hot gas it contains, which resemble feline paw pads.

SPITZER SPOTS BABY STARS

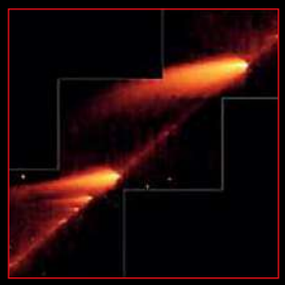
By using Spitzer to peer through thick clouds of cosmic gas and dust, astronomers discovered a population of baby stars near the centre of the Milky Way. The yellow spots show the young stars that were detected in the chaotic environment at the Milky Way's centre.

THOUSANDS OF GALAXIES

A false-colour mosaic of the Coma Cluster released in 2007 revealed thousands of new faint objects, many of which belong to the cluster. The mosaic combines visible-light data from the Sloan Digital Sky Survey (blue) with long and short-wavelength infrared views (red and green respectively) from Spitzer.

COMET BREAKUP

Comet 73P/Schwassmann-Wachmann began fracturing in 1995. The breakup accelerated in 2016 as the comet approached the Sun, as it does every 5.3 years. Spitzer returned an infrared image of the scene, revealing three dozen chunks in addition to a broad stripe in the sky created by smaller pebbles and dust.



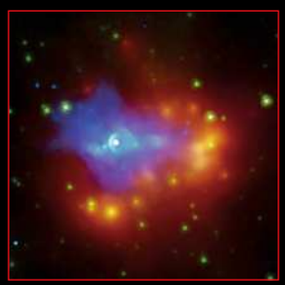
SCULPTOR GALAXY

The spectacular swirling arms and central bar of the Sculptor Galaxy are revealed in this image from Spitzer, released in 2013. Also known as NGC 253, the Sculptor Galaxy is part of a cluster of galaxies visible to observers in the Southern Hemisphere.



STELLAR CORPSE

This image from Spitzer and Chandra shows the dusty remains of a collapsed star. The composite of G54.1+0.3 shows X-rays from Chandra in blue and data from Spitzer in green and red-yellow. Scientists think that a pulsar (the white source in the centre) is sending out a wind that's heating up remnant supernova dust.





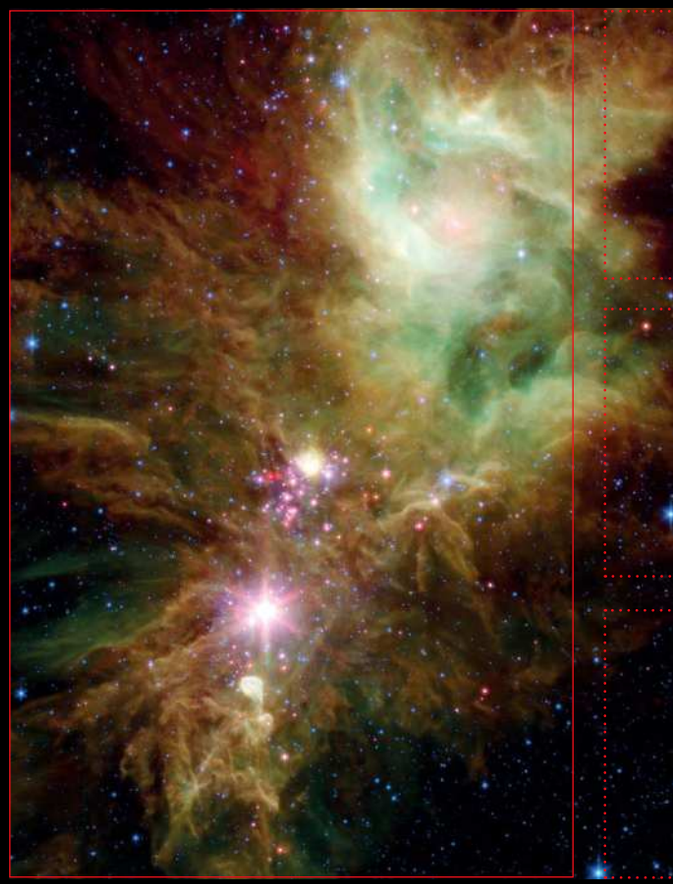
"SCIENTISTS THINK THAT A PULSAR IS SENDING OUT A WIND THAT'S HEATING UP REMNANT SUPERNOVA DUST"

ORION UNVEILED

This infrared image shows the Orion Nebula, the closest massive star-making factory to Earth.

SNOWFLAKE AND CONE

Strange shapes and textures can be found in the neighbourhood of the Cone Nebula. These patterns result from the tumultuous unrest that accompanies the formation of NGC 2264, the Snowflake Cluster. To better understand this process, a detailed image of this region was taken in two colours of infrared light.

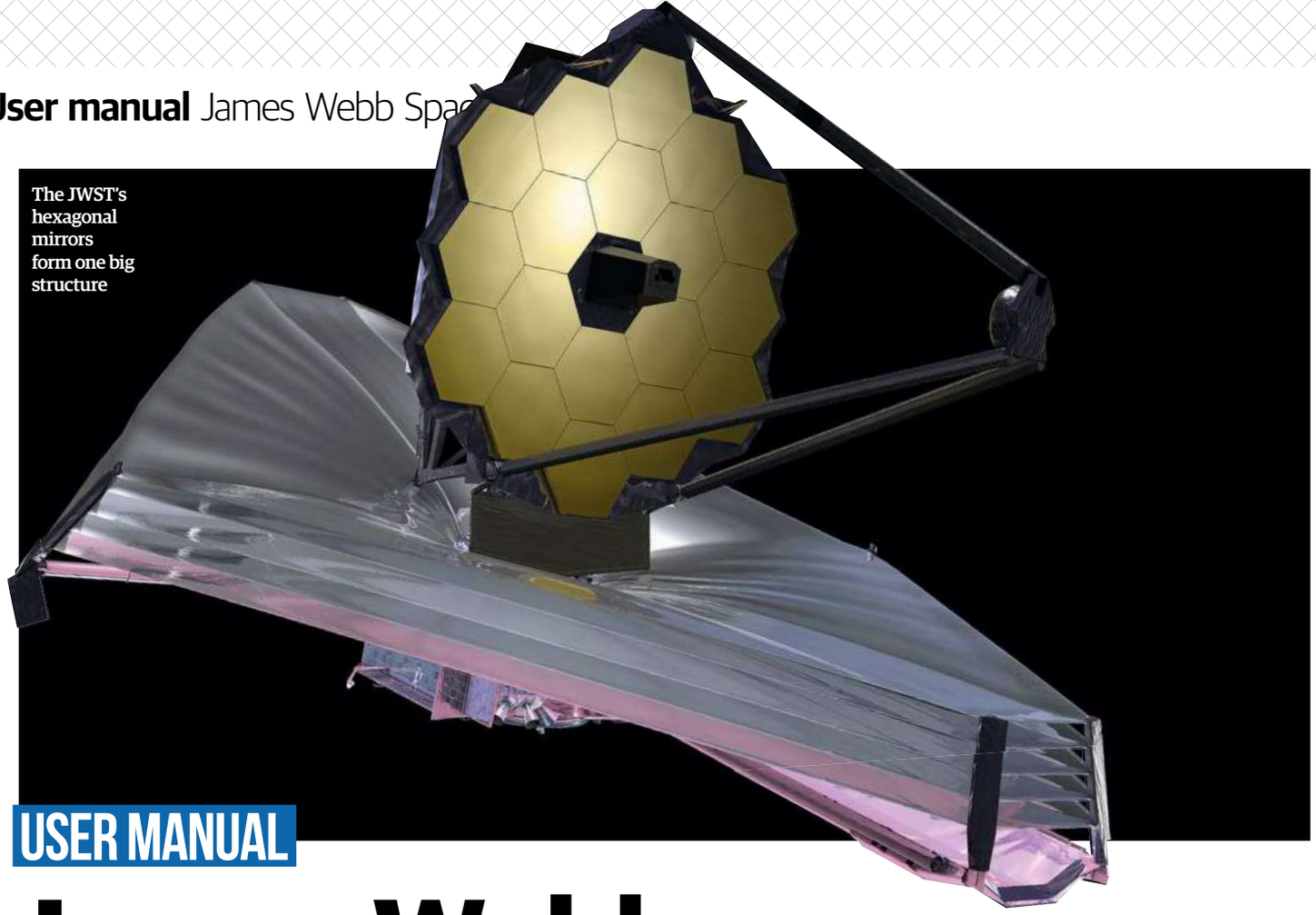


ANDROMEDA GALAXY

This infrared composite shot from NASA's Spitzer Space Telescope highlights the contrast between the Andromeda Galaxy's choppy waves of dust (red) and smooth sea of older stars (blue).



All images © NASA/JPL-Caltech



The JWST's hexagonal mirrors form one big structure

© NASA

USER MANUAL

James Webb Space Telescope

THE SPECS

Launch: 25 December 2021

Launch rocket: Ariane 5 ECA

Target: Sun-Earth L2 point

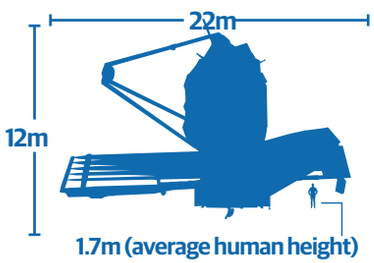
Operators: CSA, ESA, NASA and STScI

Orbital inclination: Halo orbit

Component: Multiple international components

Planned mission ends: 2031

Focal length: 131.4 metres (431 feet)



Ever since NASA launched the Orbiting Astronomical Observatory 2 spacecraft in December 1968, the scientific world has gazed out into the depths of the universe through many a generation of space telescope. For decades, two observatories have provided the most prolific and in-depth imagery of space: the Hubble and Spitzer space telescopes.

Since its launch in 1990, the Hubble Space Telescope has become an integral part of NASA's – and, by extension, the wider scientific community's – understanding of the cosmos, and in conjunction with the infrared capabilities of Spitzer, launched in 2003, our views of the star-laden skies around us have changed forever.

But like any great pioneer or innovator, the older telescopes must eventually step aside to make way for a new wave of scientific developments. And it's in the James Webb Space Telescope – named after James E. Webb, the second administrator of NASA, who helped redefine the vision of the early Space Race – that the American space agency has placed its hopes and dreams. With its 6.5-metre (21.3-foot) diameter segmented mirror, the new primary telescope it is providing a whole new level of clarity to space-captured imagery.

The James Webb Space Telescope, sometimes referred to as JWST or simply Webb, began life in the wake of Hubble's journey to scientific immortality. Four years after its launch, Hubble was proving a resounding success, so NASA began to ponder the next step for space observation. What shape would they take in the coming decades as Hubble orbited towards retirement?

In 1996, a NASA committee convened to discuss that very subject, and it soon became apparent that certain capabilities that Hubble didn't have – such as improved infrared vision – would be vital if the next generation of telescopes were to outshine the already considerably bright Hubble.

Not only that, it would have a mirror large enough to provide greater light sensitivity and the power to see further than any other telescope before it. The teams behind this early form of the JWST wanted to do the seemingly impossible – they wanted to glimpse the very first light in the universe. NASA certainly had the dream. It then needed a plan to make it a reality.

Later that year, three teams of engineers and scientists came together to etch out a plan. A mirror 4.5 metres (14.8 feet) in diameter was conceived as an ideal, if ambitious, size for the segmented mirror, and the newly dubbed Next

Anatomy of the James Webb Space Telescope

From microshutters and lightweight mirrors to cryocoolers and infrared sensors, the JWST is jam-packed with innovation and progressive tech

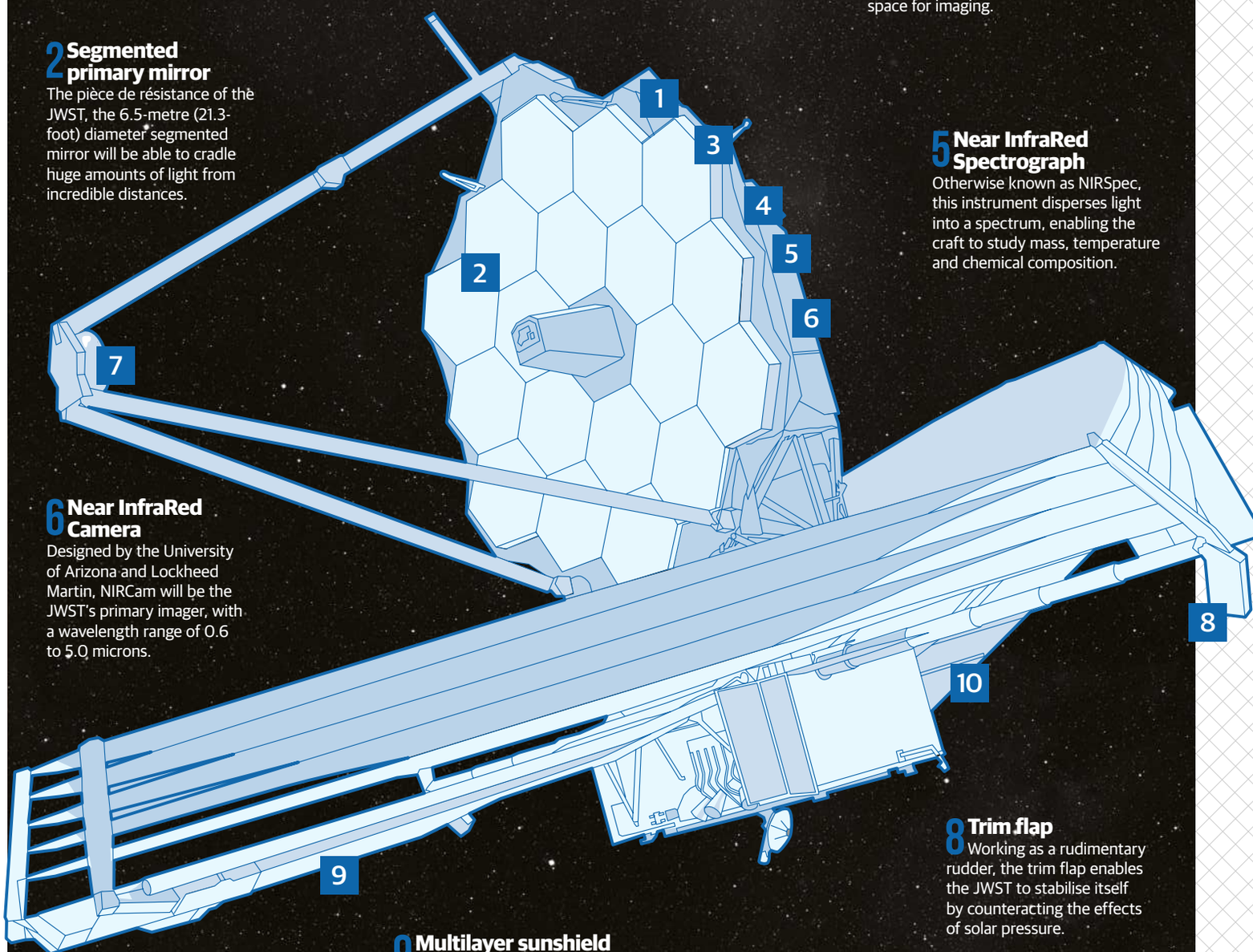
1 Integrated Science Instrument Module
Otherwise known as the ISIM, this section of the craft contains the four main scientific instruments used aboard the JWST.

2 Segmented primary mirror
The pièce de résistance of the JWST, the 6.5-metre (21.3-foot) diameter segmented mirror will be able to cradle huge amounts of light from incredible distances.

3 Mid-InfraRed Instrument
This instrument, usually referred to as MIRI, combines a camera and a spectrograph in order to detect light from distant objects that our eyes are unable to see.

4 Fine Guidance Sensor and Near Infrared Imager and Slitless Spectrograph
Provided by the Canadian Space Agency, these instruments enable the JWST to pinpoint the correct points in distant space for imaging.

5 Near InfraRed Spectrograph
Otherwise known as NIRSpec, this instrument disperses light into a spectrum, enabling the craft to study mass, temperature and chemical composition.



6 Near InfraRed Camera
Designed by the University of Arizona and Lockheed Martin, NIRCam will be the JWST's primary imager, with a wavelength range of 0.6 to 5.0 microns.

7 Secondary mirror
In conjunction with the large primary mirror, the smaller mirror reflects light from the primary mirror straight to the craft's scientific instruments.

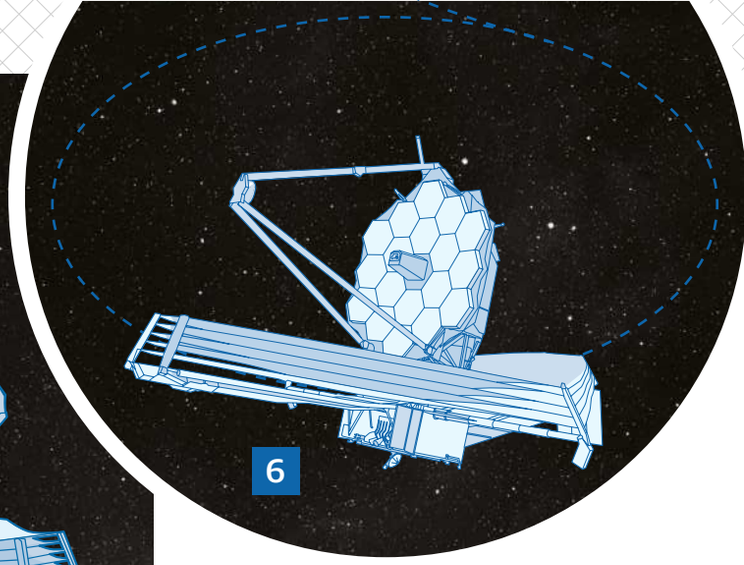
8 Trim flap
Working as a rudimentary rudder, the trim flap enables the JWST to stabilise itself by counteracting the effects of solar pressure.

9 Multilayer sunshield
The JWST is operating in considerably cold temperatures, but its position sees it regularly bombarded with heat from the Sun. Five thick layers protect the craft's mirrors and prevent its instruments from overheating.

10 Solar power array
The side of the craft facing the Sun features the solar array, which will convert sunlight to electricity in order to power the telescope.

© Adrian Mann

Unfurling the JWST



1 Ariane 5 ECA
The expendable launch vehicle carried the JWST to its space destination. It was launched from the European Spaceport located near Kourou, French Guiana.

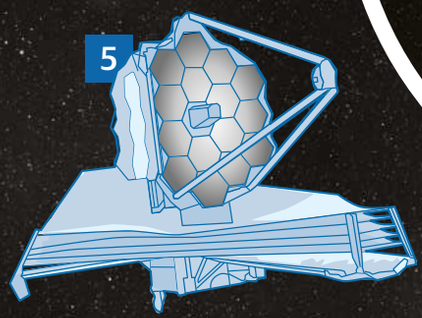
2 Solar arrays are deployed
After separating from the launch vehicle, the solar arrays and antenna were unfolded into place within ten hours of the craft taking flight.

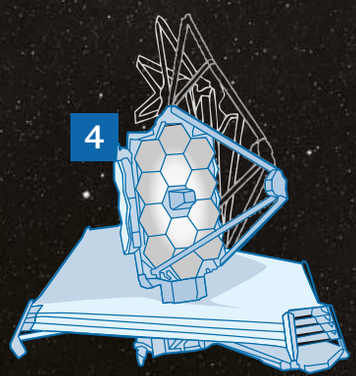
3 Sunshield is readied
Following a series of course corrections, the fore and aft (front and rear) sunshield pallets unfolded and the material of the main sunshield was pulled taut like a multilayered tarpaulin beneath the main tower.

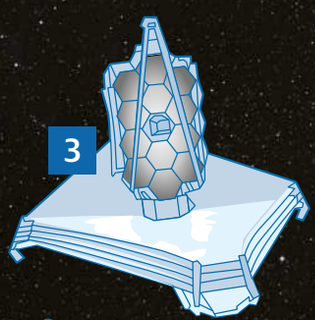
4 Secondary mirror deployed
After the onboard cryocooler activated, the secondary mirror was moved into position. This was a slow, precision process taking around ten days.

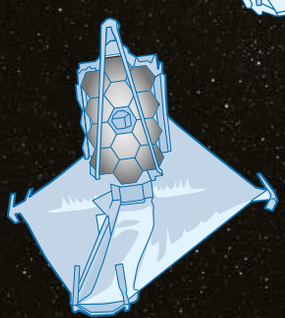
5 Main mirror is assembled
Between days 12 and 14 of navigation, the two wings of the main mirror were positioned to align with the larger mirror section facing the secondary mirror.

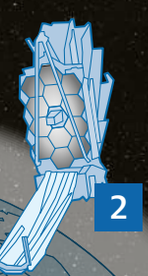
6 L2 point orbit begins
Once in its final orbital position roughly 1.4 billion kilometres or 871 million miles from Earth, the fully assembled JWST began its halo orbit at the L2 point.

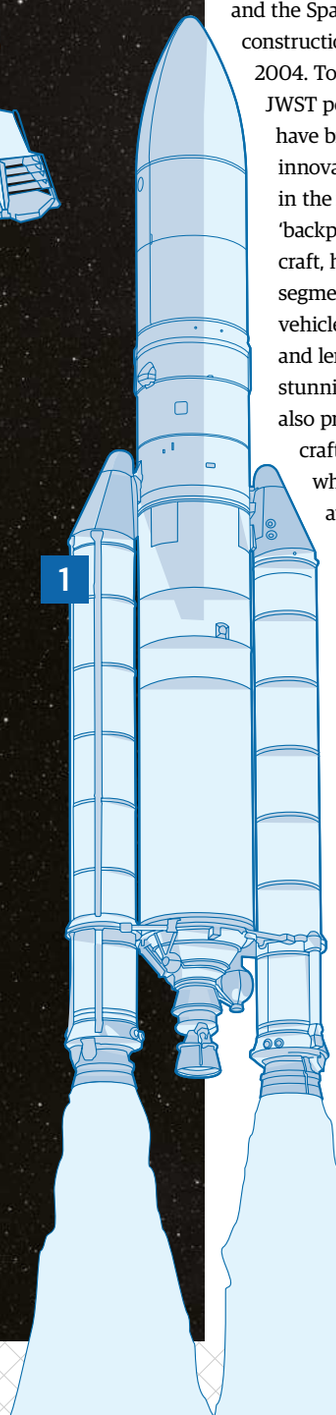












Generation Space Telescope (NGST) was born. Over the next six years, various refinements were made to its design, including a change of name in 2002 to honour the man who had been at the forefront of the iconic Apollo missions. Designed and overseen in cooperation with the European Space Agency (ESA), Canadian Space Agency (CSA) and the Space Telescope Science Institute (STScI), construction of the JWST began in earnest in 2004. To make NASA's ambitious plans for the JWST possible, the agency and its partners have brought together some of the most innovative technologies currently available in the industry. The craft has a colossal 'backpane' that serves as the spine for the craft, holding the giant 6.5-metre (21.3-foot) segmented mirror and ensuring the whole vehicle remains motionless while its mirrors and lenses work together to capture each stunning image. This section of the craft also provides a vital means of regulating the craft's temperature – an important factor when you consider that it's operating at around -225 degrees Celsius (-370 degrees Fahrenheit).

Those mirrors form the most essential part of the JWST – in order to see the remains of the universe's birth, over a staggering 13 billion light years away, the mirror in question would have to be big enough to collect every last drop of light. However, a huge mirror means considerable weight, so the JWST teams have created one from 18 hexagonal segments, with each one crafted from beryllium and

"THOSE MIRRORS FORM THE MOST ESSENTIAL PART OF THE JWST"

x4 Images © Adrian Mann

coated in gold to improve its reflection of infrared light. Each individual segment weighs as little as 20 kilograms, and they all fit together to create one giant instrument.

So what does the future hold for the JWST? It's already shaping up to be a big year for the craft after its first image was released in July 2022. Its mirror alignment was a complex seven-stage operation, performed while the rest of its instrumentation was also going through its calibration procedures. So far it has shown us images includinng distant nebulae and views of Jupiter. With a team of over 1,000 people from over 17 countries involved, the JWST has been a long time coming, but its mission to capture the first light of the universe has galvanised those involved, and promises to be one of the most exciting developments in modern space engineering.



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HOW TO...

Take photos from the L2 Lagrange point

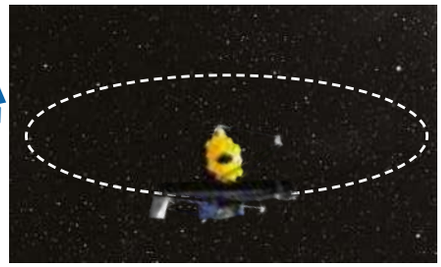
1 Building up energy

After around 30 days of travel, the JWST needed to build up enough energy to break into the gravitational pocket created between Earth and the Sun. To do this it performed a small loop – this created a slingshot that launched the rocket into orbit at the L2 point.



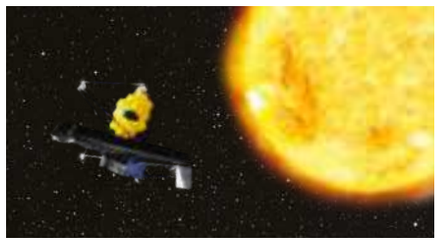
2 Staying in place

Once it breached the gravitational pocket of the L2 point, the JWST has to keep itself in place so that it can commence searching for the first light of the universe.



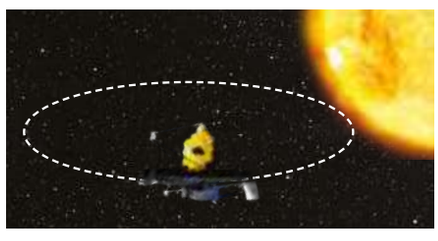
3 Maintaining direction

The back of the craft must always be facing the Sun to protect the sensitive instruments and mirrors at the front. This positioning is also vital for keeping the JWST functioning. All that sunlight isn't going to waste, as the solar panel at the rear converts it into electrical power.



4 Never losing track

The JWST won't enter the shadow of Earth and lose sight of its targets. Instead the telescope will perform its halo orbit every six months. It can capture images and data without being hindered by the position of Earth and the Moon.

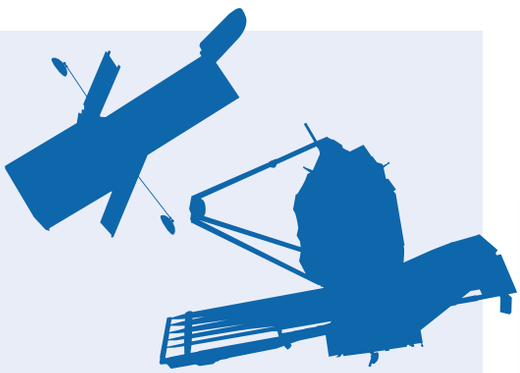


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Head to head

Hubble vs JWST

Hubble and the JWST couldn't be any more different. Hubble studies space in optical and ultraviolet wavelengths, while the JWST focuses on infrared, which enables it to pierce thick clouds of space dust. Hubble is 13.2 metres (43.3 foot) in length – the size of a bus – but the JWST is huge in comparison. The sunshield alone is 22 by 12 metres (72 by 39 feet) – roughly the size of a tennis court.



Hubble 11,110kg

JWST 6,500kg

TOP TECH

The JWST sunshield

In order for the JWST's instruments to operate, they need to be cooled to below -223 degrees Celsius (-370 degrees Fahrenheit). To detect emissions from astronomical objects, the JWST employs a sunshield that blocks out the Sun's damaging heat and radiation while it conducts a halo orbit. The sunshield consists of five layers of Kapton, a kind of polyimide film, coated in aluminium and doped silicon, which reflects the heat of the Sun away from the craft.



© NASA

Vital statistics

6,500KG = The total mass of the rocket and payload at launch

TEN YEARS = The initial mission time for the JWST

46-52 METRES = The length of the Ariane 5 ECA rocket that carried the JWST

705KG = The mass of the JWST's segmented primary mirror

Instant expert

WHY ARE WE STILL SEARCHING FOR INTELLIGENT ALIEN LIFE?

Should we widen our search criteria when looking for extraterrestrials?

Humans have long scanned the heavens for signs of other advanced civilisations in the universe. And we've found nothing. Absolutely nothing. So maybe we shouldn't be so focused on intelligent life, but on any sort of life whatsoever. Sure, a tiny microbe may not be as exciting as swapping stories with distant aliens, but signs of non-intelligent life may be much more common – and much easier to find – in our galaxy.

Life, including intelligent life, evolved here on Earth. Yet there shouldn't be anything particularly remarkable about our planet; it's just another random world in the galaxy. So if intelligent life happened here, it must be pretty common – widespread enough that we should be seeing signs of alien civilisations all over the place. So, where is everybody? This is the heart of the infamous Fermi paradox, and it's the main argument used to fuel the search for extraterrestrial intelligence (SETI). At first glance, it seems immediately obvious that we should not be alone in the universe, and so if we look hard enough, we should see some evidence for intelligence.

Perhaps aliens are blasting radio signals for us to listen to. Perhaps they're just generally blasting the radio, and we happen to pick it up. Perhaps they've left artefacts in the Solar System, designed to monitor us or just hang around. Perhaps they'll engage in mega-engineering projects, like enclosing their star in a swarm of solar panels. Or perhaps they'll just play around and contaminate their star with heavy metals to announce their presence. After over half a century of SETI, however, we've found nothing. No radio signals. No artefacts. No mega-engineering. To date, after over a hundred dedicated searches, we have absolutely no evidence for any intelligent life in our galaxy, or even in the universe.

BIO

PAUL M. SUTTER



Sutter is a research professor in astrophysics at the Institute for Advanced Computational Science at Stony Brook University and a guest researcher at the Flatiron Institute in New York City. He is also the author of two books: *Your Place in the Universe* and *How to Die in Space*.

"SIGNS OF NON-INTELLIGENT LIFE MAY BE MUCH MORE COMMON – AND MUCH EASIER TO FIND – IN OUR GALAXY"

SHOULD WE LOWER OUR STANDARDS?

Perhaps we should just search for extraterrestrial life, rather than focusing on advanced alien civilisations. That means any kind of life: single-celled organisms floating in oceans, moss clinging to rocks or the first hints of complex creatures moving around their environments. Sure, these kinds of life forms may not be as loud as intelligent life, but that doesn't make them invisible. Indeed, one of the key features of any kind of life is the ability to throw a planet out of equilibrium.

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FIRST CONTACT

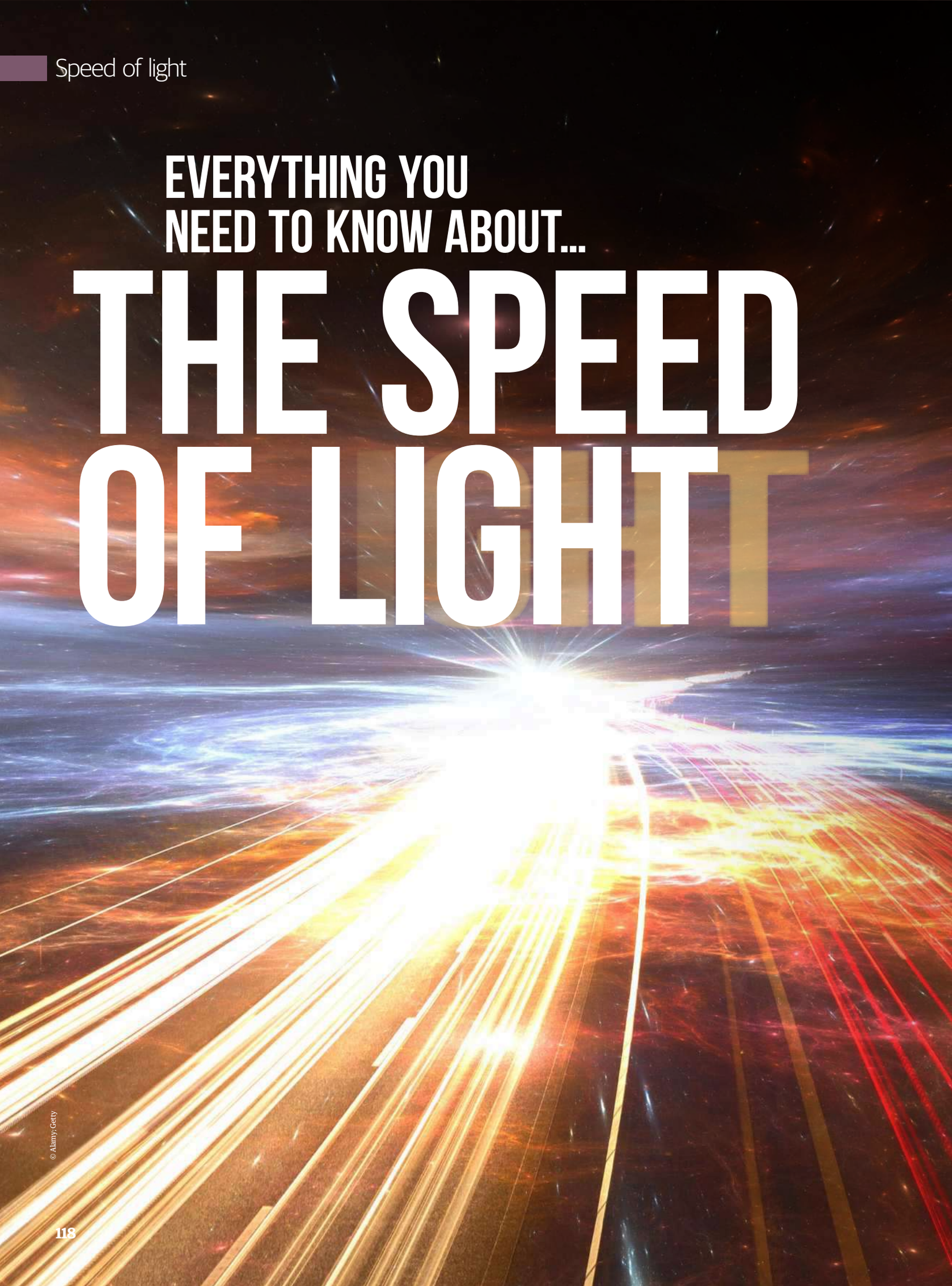
Our current technology limits us to studying the atmospheres of giant planets orbiting close to their parent stars. But NASA's Transiting Exoplanet Survey Satellite is cataloguing a number of promising candidates for follow-up studies with the James Webb Space Telescope, which will have the capability to detect an overabundance of oxygen in the atmospheres of alien worlds. As first-contact scenarios go, it may not be that exciting. It's likely our first evidence for life outside Earth will take the form of a wiggle in a line on a plot, telling us that living creatures have dramatically altered the equilibrium of their home planet.

SETI ASSUMPTION

The assumption behind SETI is that intelligent life should be easier to detect than regular life, because intelligent creatures are capable of making their presence known. But something in this argument is going wrong. Either intelligent life isn't as common as we might have hoped, or it's not as detectable as we might have hoped.

ATMOSPHERIC CLUES

Our planet probably formed with a good deal of oxygen; there's plenty of it in the universe to go around. But oxygen is highly volatile and reactive, and it doesn't really last long on its own in an atmosphere – it either escapes into space or binds with other elements and turns into other things, like carbon dioxide or silicon dioxide. But around 2 billion years ago, a planet full of single-celled photosynthetic organisms ate enough carbon dioxide and burped out enough oxygen to completely revamp Earth's atmosphere, giving it substantially more oxygen than it would have in equilibrium. Life on Earth changed the very character of this planet's atmosphere. And that's detectable elsewhere.



EVERYTHING YOU NEED TO KNOW ABOUT...

THE SPEED OF LIGHT

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THE SPEED OF LIGHT IS THE SPEED LIMIT OF THE UNIVERSE... OR IS IT?

Reported by Vicky Stein and Daisy Dobrijevic

Light travelling through a vacuum moves at 299,792,458 metres (983,571,056 feet) per second - a universal constant known in equations as 'c', or the speed of light. According to Einstein's theory of special relativity, nothing in the universe can travel faster than light. The theory states that as matter approaches the speed of light, that matter's mass becomes infinite. That means the speed of light functions as a speed limit on the whole universe.

The speed of light is so immutable that it's used to define international standard measurements like the metre. Through some crafty equations, it also helps define the kilogram and the Kelvin. But despite the speed of light's reputation as a universal constant, scientists and science-fiction writers alike spend time contemplating faster-than-light travel. So far, no one's been able to figure out how to travel at such speed. But that hasn't slowed our collective hurtle towards new stories, new inventions and new realms of physics

A light year is the distance light can travel in one year - about 10 trillion kilometres (6 trillion miles). It's one way astronomers and physicists measure immense distances across our universe. Light travels from the Moon to our eyes in about one second, which means the Moon is about one light second away. Sunlight takes about eight minutes to reach our eyes, so the Sun is about eight light minutes away. Light from Alpha Centauri, the nearest star system to our own, requires roughly 4.3 years to get here, so Alpha Centauri is 4.3 light years away.

"THE SPEED OF LIGHT IS SO IMMUTABLE THAT IT IS USED TO DEFINE INTERNATIONAL STANDARD MEASUREMENTS LIKE THE METRE"

Stars and other objects beyond our Solar System lie anywhere from a few light years to a few billion light years away. When astronomers study objects that are far away, the objects appear as they existed at the time the light left them. This principle allows astronomers to see the universe as it looked after the Big Bang, about 13.8 billion years ago. Objects that are 10 billion light years away appear to astronomers as they looked 10 billion years ago, rather than how they appear today.

As early as the 5th century CE, Greek philosophers like Empedocles and Aristotle disagreed on the nature of light speed. Empedocles thought that light, whatever it was made of, must travel, and must have a rate of travel. Aristotle wrote a rebuttal of Empedocles' view in his own treatise, *Sense and Sensibilia*, arguing that light, unlike sound and smell, is instantaneous. Aristotle was wrong, but it would take hundreds of years for anyone to prove it.

In the mid-1600s, Italian astronomer Galileo Galilei stood two people on hills less than a mile apart. Each person held a shielded lantern. One uncovered their lantern; when the other person saw the flash, they uncovered theirs. But Galileo's experimental distance wasn't far enough for his participants to record the speed of light. He could only conclude that light travelled at least ten times faster than sound.

In the 1670s, Danish astronomer Ole Rømer tried to create a reliable timetable for sailors at sea, and accidentally came up with a new best estimate for the speed of light. To create an astronomical clock, he recorded the precise timing of eclipses of Jupiter's moon Io from Earth. Over time, Rømer observed that Io's

$E=MC^2$ EINSTEIN'S EQUATION EXPLAINED

Einstein's investigation of the way that mass increases as an object attempts to accelerate near the speed of light revealed this simple but elegant equation that lies at the heart of all modern physics. Here, E is a body's energy content, m its mass and c the speed of light, a universal constant. It can be used to compare a body's rest mass and energy – excluding energy due to motion – or its total relativistic mass and energy, including energy due to motion.

The idea that mass and energy are interchangeable in extreme circumstances lies at the heart of modern physics. It explains the power source for all stars, where nuclear fusion of light elements into heavier ones converts a small excess of mass directly into energy, and the origin of matter in the universe itself, where enormous amounts of energy released in the Big Bang coalesced into subatomic particles, which then went on to form atoms.



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"MICHELSON'S RESULT WAS ACCEPTED AS THE MOST ACCURATE MEASUREMENT OF THE SPEED OF LIGHT FOR 40 YEARS, UNTIL MICHELSON REMEASURED IT HIMSELF"

MASS INCREASES WITH SPEED

Setting the speed of light as a universal speed limit led Einstein to his remarkable discovery that mass and energy are equivalent. He arrived at this by considering what would happen if an object travelling at relativistic speed continued to pour energy into acceleration. The energy could be provided internally, for instance on a rocket powered by an ion engine, or externally, for example in a particle accelerator.

Einstein realised that in either case the object's kinetic energy would have to increase even if its velocity could not. Since kinetic energy is reliant on both mass and velocity, this indicated that adding energy to an object moving at near-light speed tends to increase its mass. In fact, Einstein found that the energy content of an object is equal to its mass times the speed of light, or c, squared.

Above: The Hubble Space Telescope captured this image of the spiral galaxy NGC 3972, located 65 million light years from Earth in the constellation of Ursa Major

eclipses often varied from his calculations. He noticed the eclipses appeared to lag most when Jupiter and Earth were moving away from one another, showed up ahead of time when the planets were approaching and occurred on schedule when the planets were at their closest or farthest points. In a leap of intuition, he determined that light was taking measurable time to travel from Io to Earth. Rømer's calculations put the speed of light at about 200,000 kilometres (124,000 miles) per second.

In 1728, English physicist James Bradley based a new set of calculations on the change in the apparent position of the stars due to Earth's travels around the Sun. He estimated the speed of light at 301,000 kilometres (185,000 miles) per second – accurate to within about one per cent of the real value. Two new attempts in the mid-1800s brought the problem back to Earth. French physicist Hippolyte Fizeau set a beam of light on a rapidly rotating toothed wheel, with a mirror set up eight kilometres (five miles) away to reflect it back to its source. Varying the speed of the wheel allowed Fizeau to calculate how long it took for the light to travel to the adjacent mirror and back. Another French physicist, Leon Foucault, used a rotating mirror rather than a wheel to perform essentially the same experiment. The two independent methods each came within about 1,609 kilometres (1,000 miles) per second of the speed of light.

Another scientist who tackled the speed of light mystery was Poland-born Albert A. Michelson. In 1879 he attempted to replicate Foucault's method of determining the speed of light, but Michelson increased the distance between mirrors and used extremely high-quality mirrors and lenses. Michelson's result of 299,910 kilometres (186,355 miles) per second was accepted as the most accurate measurement of the speed of light for 40 years, until Michelson remeasured it himself.

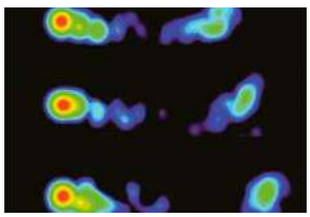
In his second round of experiments, Michelson flashed lights between two mountaintops with carefully measured distances to get a more precise estimate. In his third attempt, just before his death in 1931, he built a 1.6-kilometre (one-mile) depressurised tube of corrugated steel. The pipe simulated a near-vacuum that would remove any effect of air on light speed for an even finer measurement, just slightly lower than the accepted value of the speed of light today. Michelson also studied the nature of light itself. The best minds in physics at the time of Michelson's experiments were divided: was light a wave or a particle?

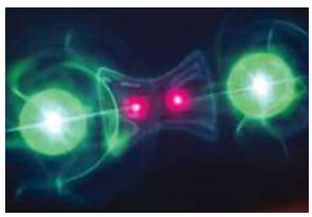
Michelson, along with his colleague Edward Morley, worked under the assumption that light moved as a wave, just like sound. And just as

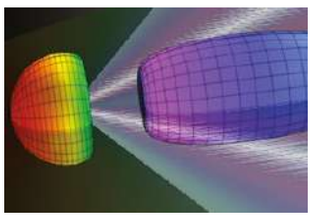
FOUR THINGS THAT BREAK THE SPEED LIMIT OF THE UNIVERSE

Einstein predicted that nothing with mass could move faster than light, but there are objects disobeying the laws of physics


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SUPERLUMINAL MOTION

Black holes spit out high-speed jets of particles that appear to travel faster than light. This 'superluminal' motion is an optical illusion that occurs when jets moving close to light speed are pointing roughly in our direction. Because the radiation emitted at points along the jet's path isn't moving much faster than the jet itself, the light is compressed – light emitted at different points over the course of a century reaches Earth in just a few years, creating the impression of faster-than-light motion.

ENTANGLEMENT

In quantum physics, particles with entangled properties remain connected by a strange link however widely they are separated. Measuring and 'resolving' the properties of one causes the other to instantaneously resolve itself in the other direction, with no time needed for a message to travel between them. Einstein called this effect 'spooky action at a distance' – the laws of physics seem to permit it because it can't be used to send information at faster-than-light speeds.

A TACHYONIC UNIVERSE

Even if no particles with mass can travel at the speed of light itself, some physicists have pondered whether there could be a whole universe of particles that travel faster than light. Such particles, known as tachyons, would exhibit a variety of strange properties. For example, their energy would decrease as their speed increased. However, attempts to detect evidence of this strange mirror universe have so far proved unsuccessful.

CHERENKOV RADIATION

An often overlooked point is that the universe's ultimate speed limit is the speed of light in a vacuum. When light passes through transparent materials, it can slow down significantly, and sometimes particles moving through the same medium can break this artificially lowered light-speed barrier. The result is a burst of bluish-coloured Cherenkov radiation – the light equivalent of a 'sonic boom' – which can be used to detect high-speed particles such as elusive neutrinos.

DID YOU KNOW?

Travelling at the speed of light, you could whiz around the Earth 7.5 times in one second.

sound needs particles to move, Michelson, Morley and other physicists of the time reasoned light must have some kind of medium to move through. This invisible, undetectable stuff was dubbed the 'luminiferous aether'. Though Michelson and Morley built a sophisticated interferometer – a very basic version of the instrument used today at Laser Interferometer Gravitational-Wave Observatory (LIGO) facilities – Michelson couldn't find evidence of any kind of luminiferous aether whatsoever. Light, he determined, can and does travel through a vacuum. "The experiment – and Michelson's body of work – was so revolutionary that he became the only person in history to have won a Nobel Prize for a very precise non-discovery of anything," astrophysicist Ethan Siegal wrote. "The experiment itself may have been a complete failure, but what we learned from it was a greater boon to humanity and our understanding of the universe than any success would've been."

Einstein's theory of special relativity unified energy, matter and the speed of light in a famous equation: $E=mc^2$. The equation describes the relationship between mass and energy. Small amounts of mass (m) contain, or are made up of, an inherently enormous amount of energy (E). Because energy is equal to mass times the speed of light squared, the speed of light serves as a conversion factor, explaining exactly how much energy must be within matter. And because the speed of light is such a huge number, even small amounts of mass must equate to vast quantities of energy.

In order to accurately describe the universe, Einstein's elegant equation requires the speed of light to be a constant. He asserted that light moved through a vacuum, not any kind of luminiferous aether, and in such a way that it moved at the same speed no matter the speed of the observer.

If we base our understanding of physics on special relativity, the speed of light is the immutable speed limit of our universe – the fastest anything can travel.

Although the speed of light is often referred to as the universe's speed limit, the universe actually expands even faster. The universe expands at a little more than 68 kilometres (42 miles) per second for each megaparsec of distance from the observer. A megaparsec is 3.26 million light years – a really

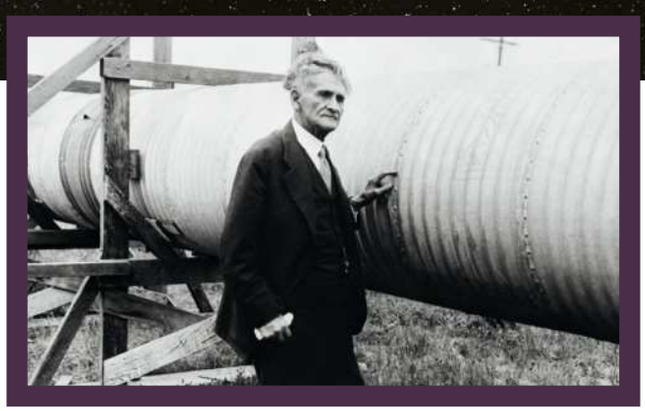

© Getty

Right: Light moves more slowly when travelling through diamond than when moving through air, and it moves through both slower than it can travel in a vacuum



TRAVELLING THROUGH SPACE AND TIME

Space travel via a wormhole relies on the fact that, according to Einstein's theory of general relativity, the three dimensions of space can be distorted by concentrations of mass, creating curves on large scales



©Getty

"SPECIAL RELATIVITY DOESN'T CARE ABOUT THE SPEED – SUPERLUMINAL OR OTHERWISE – OF A DISTANT GALAXY. AND NEITHER SHOULD YOU"

PAUL SUTTER

long way. A galaxy one megaparsec away appears to be travelling away from the Milky Way at a speed of 68 kilometres (42 miles) per second, while a galaxy two megaparsecs away recedes at nearly 136 kilometres (86 miles) per second, and so on.

"At some point, at some obscene distance, the speed tips over the scales and exceeds the speed of light, all from the natural, regular expansion of space," says astrophysicist Paul Sutter. "It seems like it should be illegal, doesn't it?" Special relativity provides an absolute speed limit within the universe, according to Sutter, but Einstein's 1915 theory regarding general relativity allows different behaviour when the physics you're examining are no longer 'local'.

"A galaxy on the far side of the universe? That's the domain of general relativity, and general relativity says who cares! That galaxy can have any speed it wants, as long as it stays way far away, and not up next to your face," Sutter says. "Special relativity doesn't care about the speed – superluminal or otherwise – of a distant galaxy. And neither should you."

Light in a vacuum is generally held to travel at an absolute speed, but light travelling through any material can be slowed down. The amount that a material slows down light is called its refractive index. Light bends when coming into contact with particles, which results in a decrease in speed. For example, light travelling through Earth's atmosphere moves almost as fast as light in a vacuum, slowing down by just three ten-thousandths of the speed of light. But light passing through a diamond slows to less than half its typical speed. Even so, it travels through the gem at over 445.8 million kilometres (277 million miles) per hour – enough to make a difference, but still incredibly fast.

Light can be trapped – and even stopped – inside ultracold clouds of atoms, and scientists have even proposed a new way to stop light in its tracks at 'exceptional points' – places where two separate light emissions intersect and merge into one. Researchers have also tried to slow down light even when it's travelling through a

1 LOCAL WORMHOLE
To allow for truly convenient interstellar travel, a wormhole would have to be located (or created) quite close to Earth.

2 DOWN THE FUNNEL
The mouth of a wormhole forms a steep-sided 'gravity well', but there's a safe entrance that avoids crossing the event horizon.

3 THROUGH THE GAP
The passage through the wormhole is 'open', forming a broad cylindrical tunnel so that the crushing gravity of the central singularity can be avoided.

4 NOT-SO-SHORTCUT?
The trip through a wormhole might be shorter, but it's still not instantaneous. Because travelling through a wormhole might still involve near-light speeds, effects such as time dilation would make the journey seem shorter.

5 SAFE PASSAGE
In theory, it's possible to steer a passage that hugs the outer edge of the wormhole to emerge at the other end.

Left: Michelson standing alongside the mile-long vacuum tube which would be used in his last and most accurate measurement of the speed of light

Right: The Alcubierre drive is a hypothetical technology that warps space to achieve faster-than-light travel

vacuum. A team of Scottish scientists successfully slowed down a single photon, or particle of light, even as it moved through a vacuum. In their measurements, the difference between the slowed photon and a 'regular' photon was just a few millionths of a metre, but it demonstrated that light in a vacuum can be slower than the official speed of light.

Science fiction loves the idea of 'warp speed'. Faster-than-light travel makes countless sci-fi franchises possible, condensing the vast expanses of space and letting characters pop back and forth between star systems with ease. But while faster-than-light travel isn't guaranteed impossible, we'd need to harness some pretty exotic physics to make it work. Luckily for sci-fi enthusiasts and theoretical physicists alike, there are lots of avenues to explore. All we have to do is figure out how to not move ourselves – since special relativity would ensure we'd be destroyed before we reached high enough speeds – but instead move the space around us. One proposed idea involves a spaceship that could fold a space-time bubble around itself.

"If Captain Kirk were constrained to move at the speed of our fastest rockets, it would take him a hundred thousand years just to get to the next star system," says Seth Shostak, an astronomer at the Search for Extraterrestrial Intelligence (SETI) Institute. "So science fiction has long postulated a way to beat the speed of light barrier so the story can move a little more quickly." Without faster-than-light travel, any *Star Trek* – or *Star Wars* for that matter – would be impossible.

If humanity is ever to reach the farthest – and constantly expanding – corners of our universe, it will be up to future physicists to boldly go where no one has gone before.

HOW LONG IS A JIFFY?
When you say you'll be somewhere in a 'jiffy', you are actually referring to a specific unit of time. For physicists, a jiffy is how long light takes to travel a distance of one femtometre – one quadrillionth of a metre.



Vicky Stein
Science journalist
Vicky holds a degree in science communication and has worked as a reporter for Stanford News Service, Space.com and LiveScience



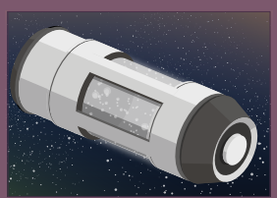
Daisy Dobrijevic
Staff Writer
Daisy is **All About Space**'s Staff Writer. She previously worked for *BBC Factual* as a researcher and *BBC Sky at Night* magazine as an editorial assistant.



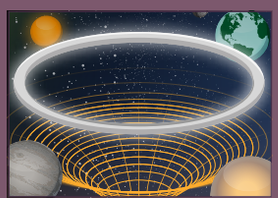
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HOW TO BUILD A WORMHOLE

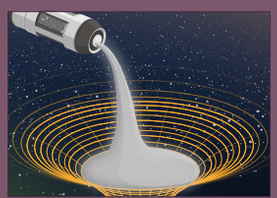
Could we build our own warp gate through space-time?



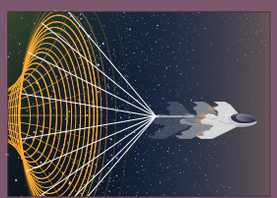
CREATE NEGATIVE ENERGY
The vital first step towards building a working wormhole would be to understand how to manufacture a source of 'negative energy' on a large scale. Although various forms of negative energy exist, there's no guarantee that a form suitable for building wormholes exists.



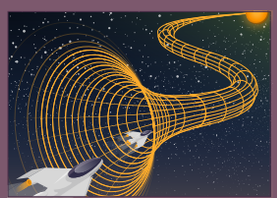
FIND A NATURAL WORMHOLE
Wormhole types depend on cosmology and particle physics. Non-traversable ones may link black holes, while microscopic ones may connect entangled quantum particles. An advanced detector would be needed to identify and 'collect' one end of a wormhole to use.



MAKE IT TRAVERSABLE
Adding negative energy would create an anti-gravitational force. In the case of a non-traversable black hole wormhole, this would draw the opening out into accessible space beyond the event horizon, while for a microscopic wormhole it could expand the tunnel to a traversable size.



FIRST TRIP
The first exploration of a newly opened wormhole would be done by a space probe. If it led somewhere safe and useful, the nearby end could be relocated closer to hand by a 'space tug' using the attractive force of gravity or repulsive 'antigravity' from the negative energy source.



COSMIC MOTORWAYS
Once a civilisation has learned how to open up one wormhole, it's easy to build a network of cosmic shortcuts. Some suggest they could even be used to build time machines, although the laws of physics mean that such a machine could not allow travel back to a time before it was created.

x5 images © Ed Crooks

Focus on

NEW SATELLITE CONSTELLATION TO TRACK GREENHOUSE GAS EMISSIONS

The new mission will monitor human-made emissions from orbit

Reported by Tereza Pultarova

A new mission will track human-made emissions of greenhouse gases from space to help keep the world on track to meet climate change mitigation targets. The new mission, announced by the European Space Agency (ESA) and the European Union's Earth-monitoring program Copernicus during the 2021 UN Climate Change Conference in Glasgow on 2 November, will rely on a dedicated constellation of satellites.

The constellation, called anthropogenic CO_2 emissions Monitoring and Verification Support Capacity (CO2MVS), is currently being developed by the ESA and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). Once in orbit, the satellites will measure concentrations of the two most common greenhouse gases, carbon dioxide and methane, in unprecedented detail and in near real time.

Carbon dioxide, which is released during fossil fuel combustion and in agriculture, is the most common climate-warming gas, accounting for nearly 80 per cent of all greenhouse gas emissions. Methane, while only accounting for about 16 per cent of global greenhouse gas emissions, is 80 times more potent in warming up Earth's atmosphere than carbon dioxide, and therefore also a cause for concern.

The new CO2MVS constellation should be up and running by 2026, in time to help the world review its progress in curbing greenhouse gas emissions as required by the Paris Agreement, the international treaty negotiated during the 2015 UN Climate Change Conference held in the French capital. That agreement requires nations to take stock of their progress every five years to ensure that countries are on track to meet their greenhouse gas reduction targets.

The first such analysis is expected to conclude by 2023; the new constellation could be part of the second, due to be completed in 2028. Copernicus representatives said that the new satellite tool will be "game-changing", allowing climate researchers to see individual sources of



Left: The constellation will be able to detect sources of emissions

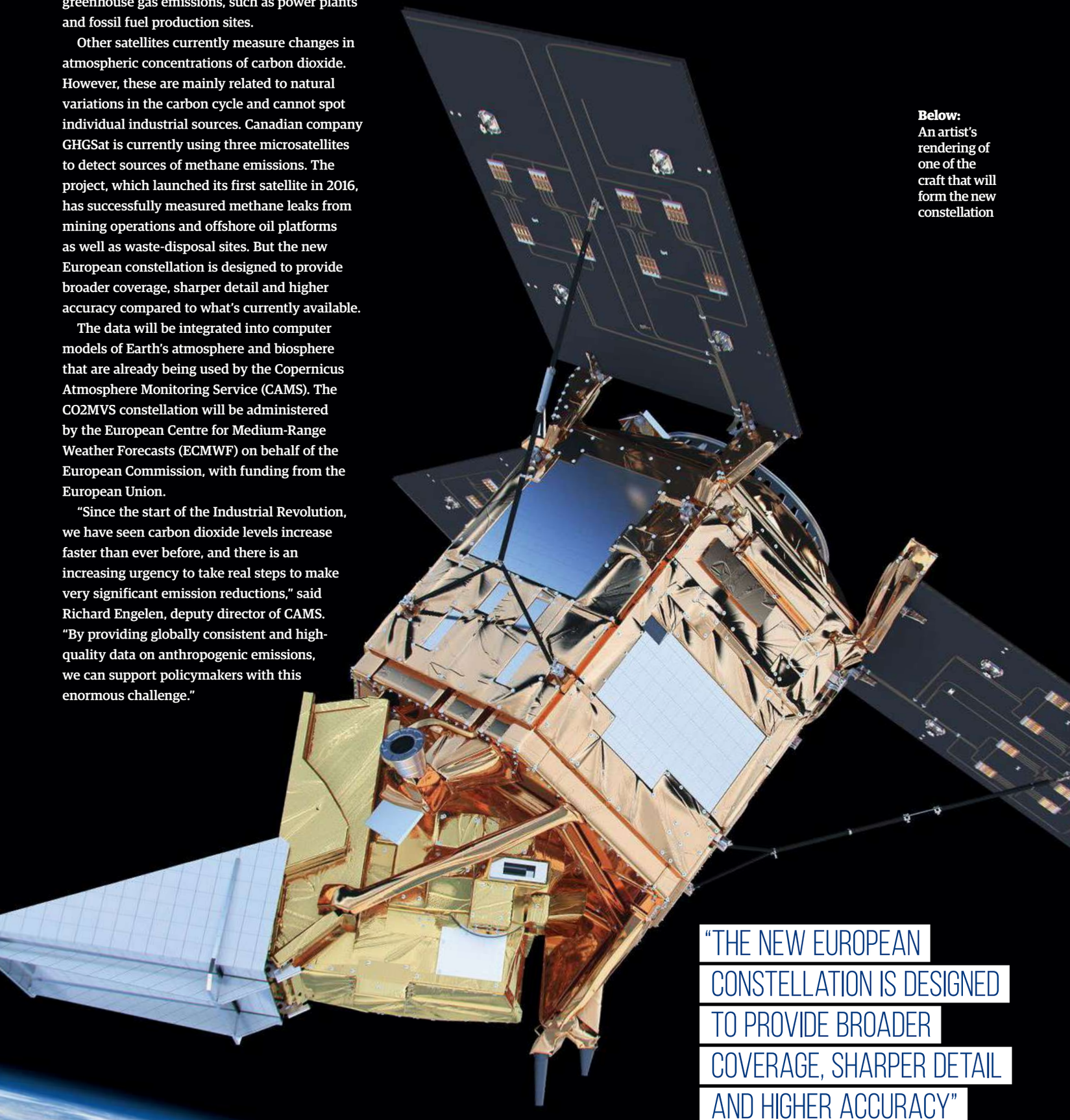
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greenhouse gas emissions, such as power plants and fossil fuel production sites.

Other satellites currently measure changes in atmospheric concentrations of carbon dioxide. However, these are mainly related to natural variations in the carbon cycle and cannot spot individual industrial sources. Canadian company GHGSat is currently using three microsatellites to detect sources of methane emissions. The project, which launched its first satellite in 2016, has successfully measured methane leaks from mining operations and offshore oil platforms as well as waste-disposal sites. But the new European constellation is designed to provide broader coverage, sharper detail and higher accuracy compared to what's currently available.

The data will be integrated into computer models of Earth's atmosphere and biosphere that are already being used by the Copernicus Atmosphere Monitoring Service (CAMS). The CO2MVS constellation will be administered by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the European Commission, with funding from the European Union.

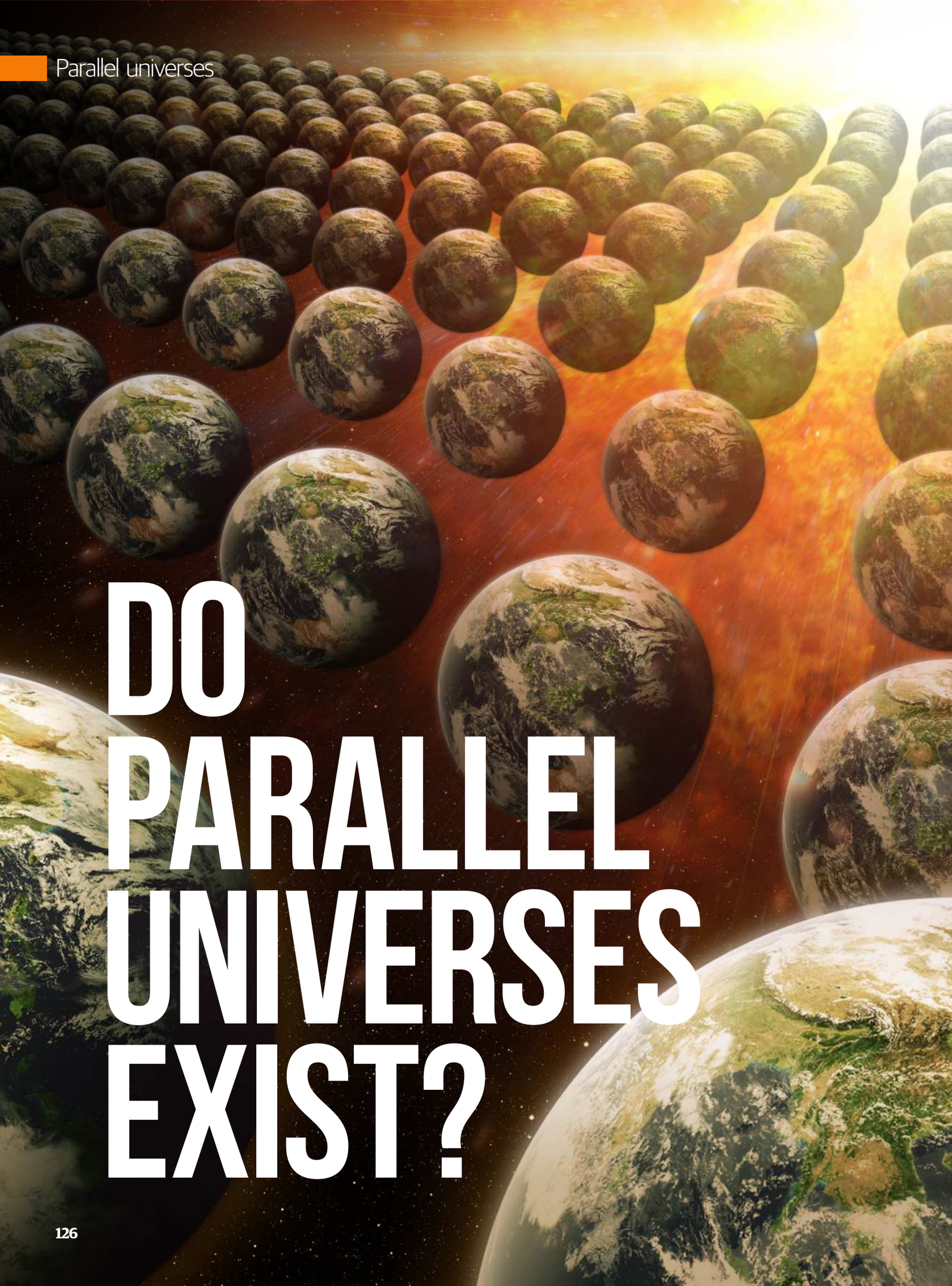
"Since the start of the Industrial Revolution, we have seen carbon dioxide levels increase faster than ever before, and there is an increasing urgency to take real steps to make very significant emission reductions," said Richard Engelen, deputy director of CAMS. "By providing globally consistent and high-quality data on anthropogenic emissions, we can support policymakers with this enormous challenge."



Below: An artist's rendering of one of the craft that will form the new constellation

"THE NEW EUROPEAN CONSTELLATION IS DESIGNED TO PROVIDE BROADER COVERAGE, SHARPER DETAIL AND HIGHER ACCURACY"

© ESA



DO PARALLEL UNIVERSES EXIST?



SCIENCE FICTION LOVES A GOOD MULTIVERSE STORY. BUT COULD WE REALLY BE IN ONE?

Reported by Vicky Stein

Our universe is unimaginably big. Hundreds of billions – if not trillions – of galaxies spin through space, each containing billions or trillions of stars. Some researchers studying models of the universe speculate that the universe's diameter could be 7 billion light years across. Others think it could be infinite. But is it all that's out there?

Science fiction loves the idea of parallel universes and the thought that we might be living just one of an infinite number of possible lives. Multiverses aren't reserved for science fiction, though. Real scientific theory explores – and in some cases supports – the case for universes outside, parallel to or distant from but mirroring our own. Multiverses and parallel worlds are often argued in the context of other major scientific concepts like the Big Bang, string theory and quantum mechanics.

Around 13.8 billion years ago, everything we know of was an infinitesimal singularity. Then, according to the Big Bang theory, the universe burst into action, inflating faster than the speed of light in all directions for a tiny fraction of a second. Before 10^{-32} seconds had passed, the universe had exploded outwards to 10^{26} times its original size in a process called cosmic inflation. And that's all before the actual expansion of matter that we usually think of as the Big Bang itself, which was a consequence of all this inflation. As the inflation slowed, a flood of matter and radiation appeared – creating the classic Big Bang fireball – and began to form the atoms, molecules, stars and galaxies that populate the vastness of space that surrounds us.

That mysterious process of inflation and the Big Bang have convinced some researchers that multiple universes are possible, or even very likely. According to theoretical physicist Alexander Vilenkin of Tufts University in Massachusetts, inflation didn't end everywhere at the same time. While it ended for everything that we can detect from Earth 13.8 billion years ago, cosmic inflation continues in other places. This is called the theory of eternal inflation. And as inflation ends in a particular place, a new bubble universe forms, Vilenkin said in 2011.

> "THE REST OF THE MULTIVERSE IS BARREN, BUT NO ONE IS THERE TO COMPLAIN ABOUT THAT"
>
> ALEXANDER VILENKIN

Those bubble universes can't contact each other because they continue to expand indefinitely. If we were to set off for the edge of our bubble, where it might butt up against the next bubble universe over, we'd never reach it because the edge is zipping away from us faster than the speed of light, and faster than we could ever travel. But even if we could reach the next bubble – according to eternal inflation and string theory – our familiar universe, with its physical constants and habitable conditions, could be totally different from the hypothetical bubble universe next to our own.

"This picture of the universe, or multiverse, as it's called, explains the long-standing mystery of why the constants of nature appear to be fine-tuned for the emergence of life," Vilenkin wrote. "The reason is that intelligent observers exist only in those rare bubbles in which, by pure chance, the constants happen to be just right for life to evolve. The rest of the multiverse remains barren, but no one is there to complain about that." Vilenkin's explanation implies that in some of the infinite bubble universes outside our own, there could be other intelligent observers. But in every instant that passes we get farther away from them, and we will never intersect.

Other researchers base their ideas of parallel universes on quantum mechanics, the mathematical description of subatomic particles. In quantum mechanics, multiple states of existence for tiny particles are all possible at the same time – a 'wave function' encapsulates all of those possibilities. However, when we actually observe subatomic particles, we only ever observe one of the possibilities. According to the Copenhagen interpretation of quantum mechanics, we observe an outcome when the wave function 'collapses' into a single reality, 'forcing' the subatomic particle to pick a state.

The many-worlds theory proposes instead that every time one state, or outcome, is observed, there is another 'world' in which a different quantum outcome becomes reality. This is a branching arrangement in which, instant by instant, our perceived universe branches into near-infinite alternatives. Those alternate universes are completely separate and unable to intersect, so while there may be uncountable versions of you living a life that's slightly – or wildly – different from your life in this world, you'd never know it.

The many-worlds theory is the most 'courageous' take on the quandary of quantum mechanics, physicist Sean M. Carroll wrote in his book, *Something Deeply Hidden: Quantum Worlds and the Emergence of Spacetime*. He also argued that it's the most straightforward theory, although not without its wrinkles. One of those wrinkles is that the many-worlds idea is not really falsifiable. This is an extremely important component of scientific thought, and is the way the scientific community develops ideas that can be explored with observation and experimentation. If there's no opportunity to find evidence against a theory – or indeed for it – that's bad for science as a whole.

Some physicists believe in a flatter version of multiple universes. That is, if the universe we live in goes on forever, there are only so many ways that the building blocks of matter can arrange themselves as they assemble across infinite space. Eventually, any finite number of particle types must repeat a particular arrangement. Hypothetically, in a big enough

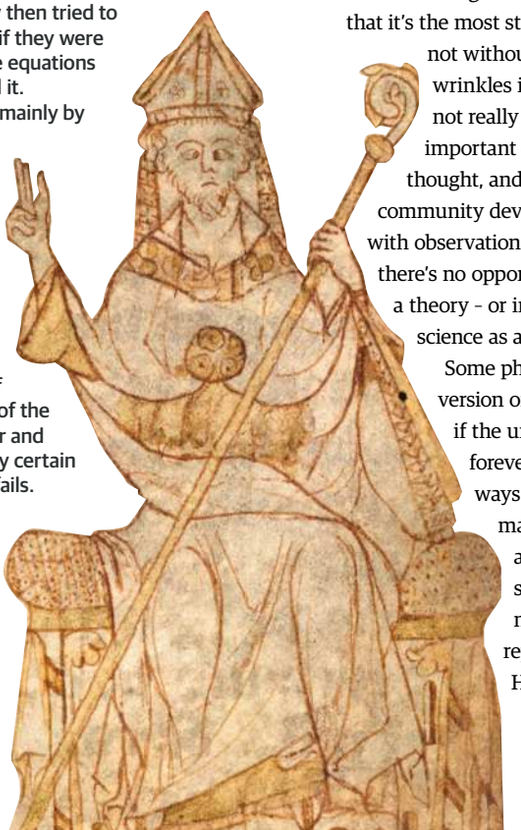
HOW A MEDIEVAL PHILOSOPHER DREAMED UP THE 'MULTIVERSE'

The idea that our universe may be one among many has intrigued modern cosmologists for some time. But this concept might have appeared, albeit unintentionally, back in the Middle Ages. When scientists analysed a Latin text and applied modern mathematics to it, they found hints that the English philosopher who wrote it in 1225 was already toying with concepts similar to the multiverse. Scientists translated the text – *De Luce*, which means 'On Light', by philosopher Robert Grosseteste – into English. They then tried to understand what he was aiming to explain, and wrote down his ideas as if they were modern mathematical equations. A team used a computer to solve these equations and to see whether they explained the universe as Grosseteste imagined it.

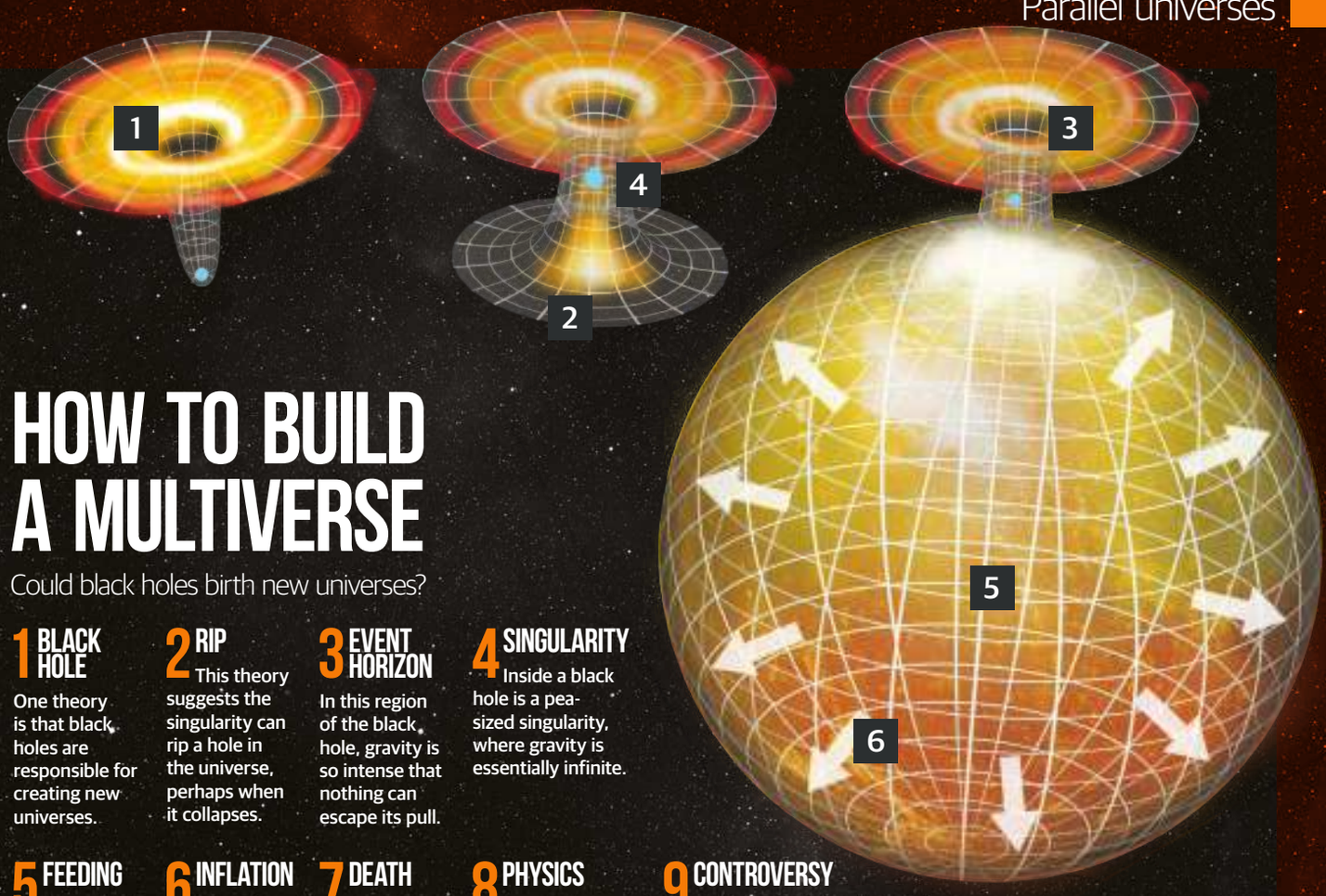
In his time, the dominant cosmological model was the one developed mainly by Aristotle. He postulated that there were nine planets (spheres), one inside the other, with Earth at the centre. Grosseteste assumed that the universe was born from an explosion that pushed everything, matter and light, out from a single point – an idea strikingly similar to the modern Big Bang theory. However, Grosseteste's reasoning only works if there's the right number of properly ordered celestial spheres, and this only happens in simulations if there are very specific starting points.

The medieval philosopher realised this problem. To deal with it, he added an extra reason to explain why there were exactly nine celestial spheres plus one – an 'imperfect' Earth. His explanation was remarkably similar to the reasoning applied in modern cosmology. Today, the laws of general relativity and quantum mechanics are used to explain the origin of the cosmos, but they don't tell us the amounts of normal matter, dark matter and dark energy in the universe. In other words, current models work for only certain specific values, and if the values are chosen at random, the explanation fails.

To satisfy these conditions, some physicists suggest that we live in a multiverse – that there is not one universe, but an infinite number of them. In this way, any outcome can be accounted for, if not in ours, then in a neighbouring universe. In the same way, if the parameters in Grosseteste's model are modified, there will be a different number of spheres around Earth. Although *De Luce* never mentions the term 'multiverse,' Grosseteste seems to realise that the model does not predict a unique solution and that there are many possible outcomes.



Source: Wikipedia Commons © Public Domain



HOW TO BUILD A MULTIVERSE

Could black holes birth new universes?

1 BLACK HOLE
One theory is that black holes are responsible for creating new universes.

2 RIP
This theory suggests the singularity can rip a hole in the universe, perhaps when it collapses.

3 EVENT HORIZON
In this region of the black hole, gravity is so intense that nothing can escape its pull.

4 SINGULARITY
Inside a black hole is a pea-sized singularity, where gravity is essentially infinite.

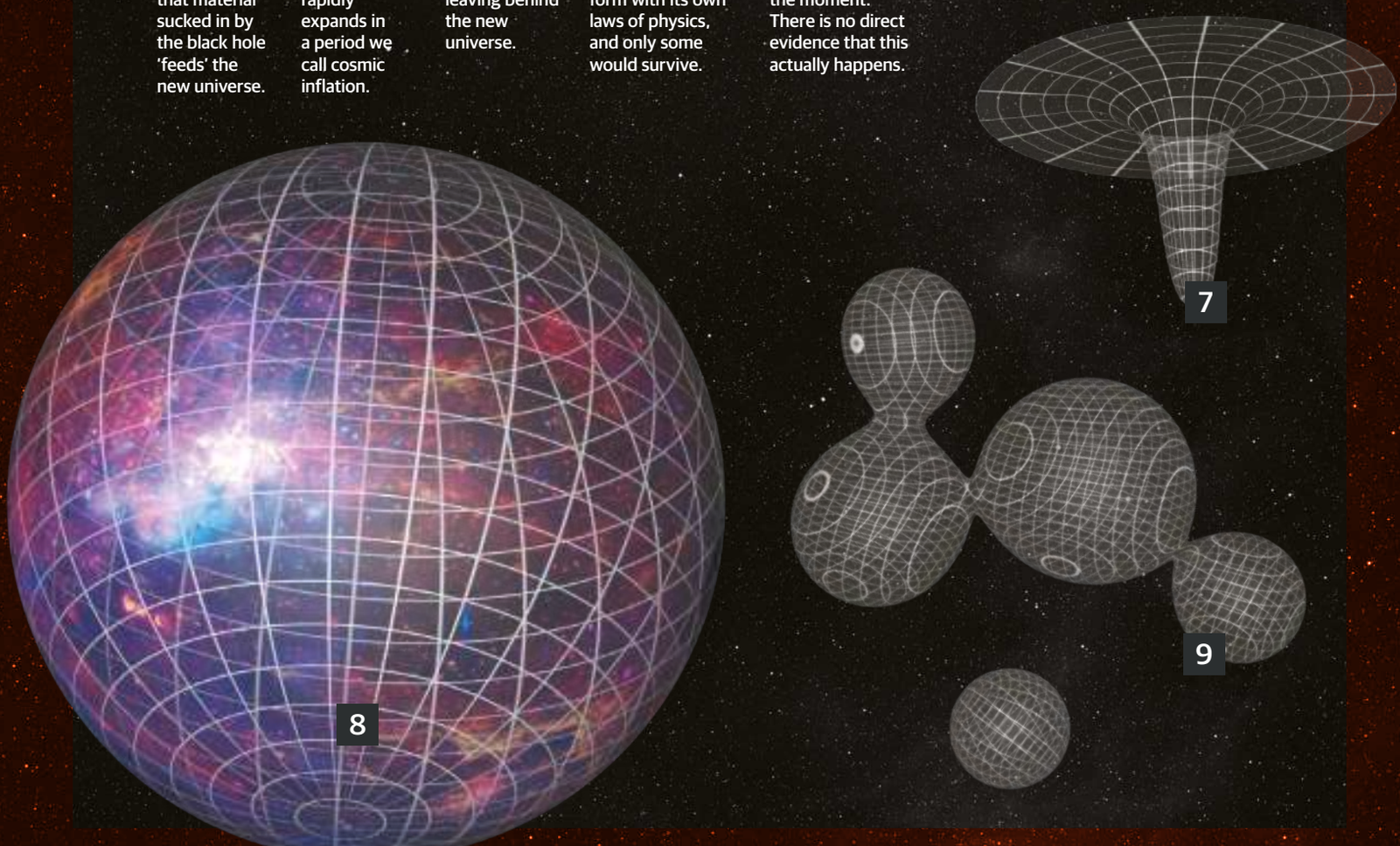
5 FEEDING
One version suggests that material sucked in by the black hole 'feeds' the new universe.

6 INFLATION
The new universe rapidly expands in a period we call cosmic inflation.

7 DEATH
The black hole collapses, leaving behind the new universe.

8 PHYSICS
Each new universe would form with its own laws of physics, and only some would survive.

9 CONTROVERSY
This is only a theory at the moment. There is no direct evidence that this actually happens.





WELCOME TO THE MULTIVERSE

1 BIG CRUNCH
Universes that fall back on themselves end in a similar state to the Big Bang. Cosmologists speculate that this kind of 'Big Crunch' could give rise to another universe in turn.

2 BIG BANG
Universes begin with a Big Bang, which may be triggered by a chance fluctuation in the quantum foam, or a collision between branes.

3 CLOSED UNIVERSE
Development of an individual universe is determined by fundamental properties such as the strength of gravity and the amount of matter contained within it.

4 RAW MATERIAL
The background fabric of the multiverse would be beyond time and space, perhaps in the form of many-dimensional 'branes', or as an all-pervading 'quantum foam'.

5 SHORT LIVED
Some universes may be so massive that the expanding force of dark energy is never able to take hold, so they collapse back onto themselves, ending in a 'Big Crunch'.

6 PERPETUAL EXPANSION
In our universe, an expansive force called dark energy seems to have grown stronger over time, overwhelming the attraction of gravity to produce an ever-growing cosmos.

7 PERPETUAL SLOWDOWN
If the forces of expansion and contraction are precisely balanced, a universe may expand ever more slowly, but will never come to a halt.

8 LONG-LIVED UNIVERSE
With less matter and mass, a universe might be able to expand to a huge size and exist for trillions of years before eventually collapsing back.



©Tobias Roetsch

Left: Perhaps a universe could exist that is an exact mirror image of our own

space, those particles must repeat arrangements as large as entire solar systems and galaxies. So your entire life might be repeated elsewhere in the universe, down to what you ate for breakfast yesterday. At least, that's thought to be the theory.

But if the universe began at a finite point – as nearly every modern physicist agrees it did – an alternate version of you likely doesn't exist, at least according to astrophysicist Ethan Siegel. As Siegel explains, "the number of possible outcomes from particles in any universe interacting with one another tends towards infinity faster than the number of possible universes increases due to inflation. So what does this mean for you?" Siegel posits. "It means it's up to you to make this universe count."

In a relatively recent addition to the pantheon of multiverse theories, researchers from the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, have proposed that the universe began at the Big Bang, and on the opposite side of the Big Bang timeline, stretching backwards in time, a universe once existed that was the exact mirror image of our own.

"Instead of saying that there was a different universe before the Big Bang, we're saying that the universe before the Big Bang is actually, in some sense, an image of the universe after the Big Bang," Neil Turok, a Perimeter Institute researcher, says. That means everything – protons, electrons and even actions like cracking an egg – would be reversed. Antiprotons and positively charged electrons would make up atoms, while eggs would uncrack and make their way back inside chickens. Eventually, that universe would shrink down, presumably to a singularity, before expanding out into our own universe. Seen another way, both universes were created at the



© NASA/ESA; Adrian Mann

"WE'RE SAYING THAT THE UNIVERSE BEFORE THE BIG BANG IS ACTUALLY, IN SOME SENSE, AN IMAGE OF THE UNIVERSE AFTER THE BIG BANG

NEIL TUROK

Big Bang and exploded simultaneously backwards and forwards in time.

Countless works of myth and fiction draw from ideas of parallel universes and the multiverse. Overlapping worlds make appearances in Norse mythology, as well as in Buddhist and Hindu cosmology. The idea of multiple universes coming into contact showed up in print as early as Edwin A. Abbott's novella *Flatland: A Romance of Many Dimensions* in 1884, and can still be seen in recent media, such as the 2016 Marvel film *Doctor Strange*. An entire genre of Japanese light novels, manga, anime and video games, called isekai, deals with characters transported to parallel worlds. Nearly every *Star Trek* series incorporates some form of mirror universe, and the 2009 reboot film starring Chris Pine and Zachary Quinto took subsequent *Star Trek* movies into an entirely new timeline that explicitly branches off from the original series. Many comics, as well as their corresponding movies, delve deeply into the idea of parallel worlds. Recent Marvel storylines – in film, TV and in print – DC's *Flashpoint* arc and 2018's *Into the Spider-Verse* all explore multiple universes and the intersections between them.

Above: This deep-field image captured by Hubble shows a small area of space in the constellation of Fornax. It shows thousands of galaxies and is one of the deepest images of the universe ever captured



Vicky Stein
Science journalist
Vicky holds a degree in science communication and has worked as a reporter for *Stanford News Service*, **space.com** and **LiveScience**

WHAT HAPPENS IN OTHER UNIVERSES?

Physicists have contemplated different levels of multiverse

LEVEL 1
WHAT HAPPENS INSIDE THIS UNIVERSE?

Everything that happens in the observable universe is repeated an infinite number of times. Also, every possible combination of events can unfold an infinite number of times. There are planets where you don't exist, but also those where you do and you're the ruling monarch of the universe or a sentient slug.

LEVEL 2
WHAT HAPPENS INSIDE THIS UNIVERSE?

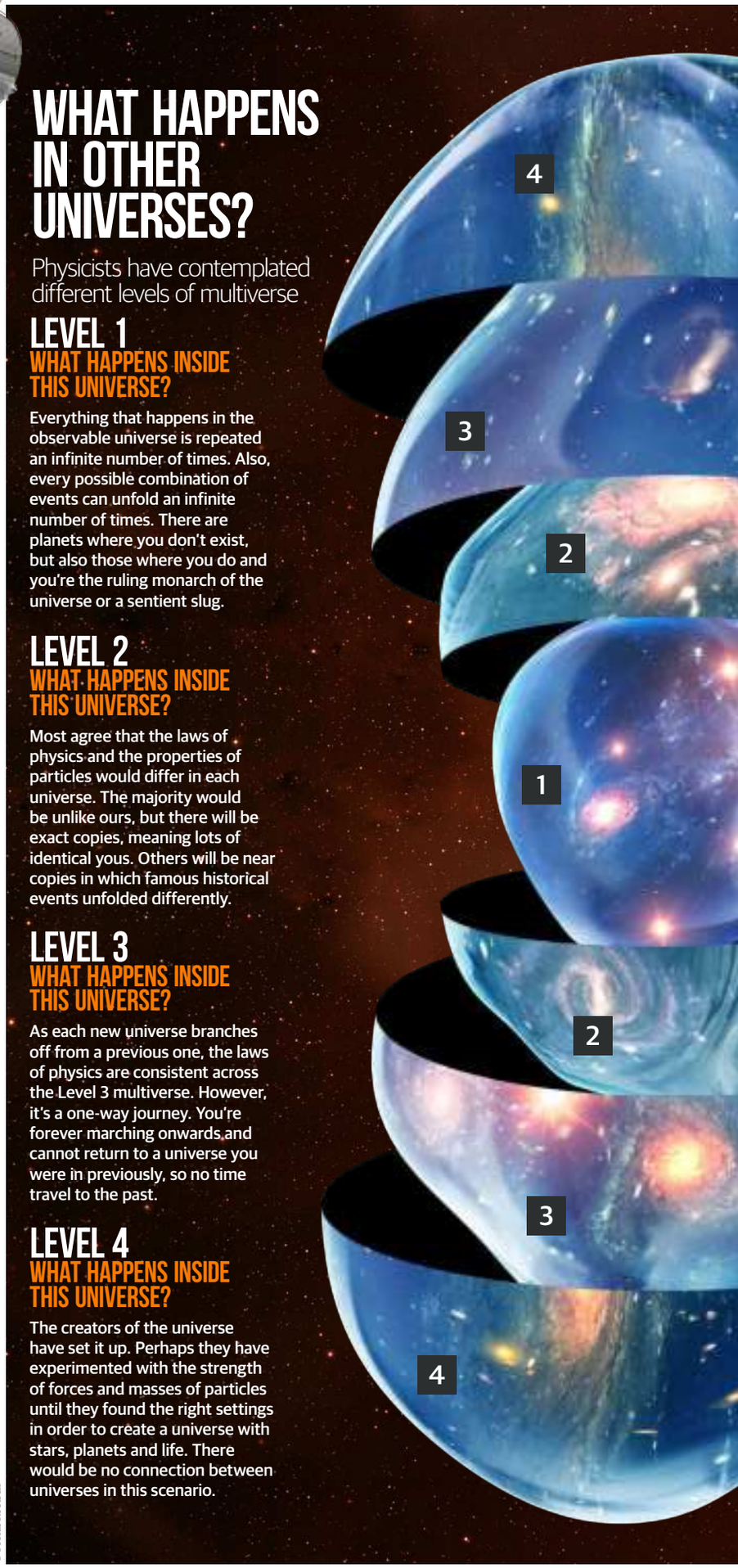
Most agree that the laws of physics and the properties of particles would differ in each universe. The majority would be unlike ours, but there will be exact copies, meaning lots of identical yous. Others will be near copies in which famous historical events unfolded differently.

LEVEL 3
WHAT HAPPENS INSIDE THIS UNIVERSE?

As each new universe branches off from a previous one, the laws of physics are consistent across the Level 3 multiverse. However, it's a one-way journey. You're forever marching onwards and cannot return to a universe you were in previously, so no time travel to the past.

LEVEL 4
WHAT HAPPENS INSIDE THIS UNIVERSE?

The creators of the universe have set it up. Perhaps they have experimented with the strength of forces and masses of particles until they found the right settings in order to create a universe with stars, planets and life. There would be no connection between universes in this scenario.



© Tobias Roetsch

‘MOON IN A JAR’ RECREATES THE HAZY ATMOSPHERE OF SATURN’S MOON TITAN

The experiment has revealed previously unknown features of the satellite’s mineral make-up

Reported by Nicoletta Lanese



©Getty

Titan is the second-largest moon in the Solar System and sports a dense atmosphere of mostly nitrogen, with a dash of methane. This yellowish haze hovers around -180 degrees Celsius (-290 degrees Fahrenheit). Below the atmosphere, lakes, seas and rivers of liquid methane and ethane cover Titan’s icy crust, particularly near the poles. And similar to liquid water on Earth, these natural gases take part in a cycle in which they evaporate, form clouds and then rain down on the moon’s surface.

Titan’s dense atmosphere, surface liquid and seasonal weather cycles make the frigid moon somewhat similar to Earth, and like our planet, the moon is known to have organic molecules that contain carbon, hydrogen and oxygen. Because of the organic chemistry taking place on Titan, scientists think the moon could serve as a massive laboratory to study chemical reactions that occurred on Earth before the emergence of life on the planet. But only one spacecraft, Cassini, has observed Saturn and its moons in detail, making it tough to do earthbound research on the wacky chemistry found on Titan. So a team of scientists set out to simulate Titan in a test tube.

The team first placed liquid water in small glass cylinders and cranked down the temperature to Titan-like conditions. This water froze to mimic Titan’s icy crust. The team then introduced ethane to the tube, which became liquid like the lakes on Titan’s surface. Finally, they added nitrogen to stand in for Titan’s atmosphere, varying the temperature of the tube ever so slightly to simulate the variations in temperature on Titan’s surface and in different layers of its atmosphere.

The team then added two compounds called acetonitrile (ACN) and propionitrile (PCN). Data from Cassini suggests that these compounds are abundant on Titan, the experiment’s principal investigator Tomče Runčevski, an assistant professor in the Department of Chemistry at Southern Methodist University in Dallas, said.

Most of the previous studies examined these two compounds separately in their pure forms, but Runčevski’s team wanted to see what would occur when the compounds mixed and mingled, as they might on Titan. As opposed to working with each compound separately, “if you mix them together there might be a completely different outcome in structure, so how the molecules will organise, and how the molecules will crystallise,” or phase into a solid form, Runčevski said.

The team found that when both are present in Titan-like conditions, ACN and PCN behave quite differently than either compound in isolation: the temperatures at which the compounds



Below: An artist's impression showing the surface of Titan

"THE TEMPERATURES AT WHICH THE COMPOUNDS MELTED OR CRYSTALLISED SHIFTED DRASTICALLY."

melted or crystallised shifted drastically. These melting and crystallisation points would be relevant in Titan's hazy, yellow atmosphere. The various layers of the atmosphere differ in temperature depending on their altitude above the moon's surface, so to understand how chemicals behave throughout the haze, the new study suggests that these temperature variations need to be taken into account, Runčevski said.

In addition, the team found that when ACN and PCN crystallise, they adopt different crystal structures depending on whether they're alone or in the presence of the other compound. Crystals form when the individual molecules within a compound snap into a highly organised structure. While the building blocks of that structure – the molecules – remain the same, depending on factors such as temperature, they can end up snapping together in slightly different configurations, Runčevski explained.

These variations in crystal structure are known as 'polymorphs'. When on their own, ACN and PCN adopt one polymorph at high temperatures and another at low temperatures. "What we notice is that if we have a mixture, the stability of the high-temperature and low-temperature [polymorphs] can be, in a way, switched," Runčevski said.

These fine details of when and how the compounds achieve a stabilised structure "can really change our understanding of what kinds of minerals we might encounter on Titan" in terms of what polymorphs they likely adopt on the moon, he continued. This can then shape what chemical reactions take place between these and other compounds on Titan.

The new study is limited in that it doesn't account for all of the chemicals present on Titan, and so can capture only a simplified picture of what actually happens on the moon. "It's important for us as scientists on Earth to create these models with increasing complexity, and one day to reach models that are really significant and can really help us further understand the surface of Titan," Runčevski said.

NASA's Dragonfly mission, set to launch in 2027 and arrive at Saturn around 2034, may provide more on-the-ground information about the mineral make-up of Titan. However, Runčevski suspects that the crystals his team observed likely form around the edges of Titan's lakes, cropping up as the liquid ethane in the lakes evaporates, leaving those compounds behind on the shoreline. At this stage, it's unclear whether the Dragonfly mission might focus on this specific aspect of the Titanian environment, but "nonetheless [the mission] is super exciting, and we will learn so much more about Titan," Runčevski said.

CHINA BUILDS AN 'ARTIFICIAL MOON' FOR GRAVITY EXPERIMENTS

The new experiment was inspired by a levitating frog

Reported by Ben Turner

Chinese scientists have built an 'artificial Moon' research facility that will enable them to simulate low-gravity environments using magnetism. The facility, launching this year, will use powerful magnetic fields inside a 60-centimetre (23.6-inch) diameter vacuum chamber to make gravity 'disappear'. The scientists were inspired by an earlier experiment that used magnets to levitate a frog. Ruilin Li, a geotechnical engineer at the China University of Mining and Technology, said that the chamber, which will be filled with rocks and dust to imitate the lunar surface, is the "first of its kind in the world" and that it could maintain such low-gravity conditions for "as long as you want."

Scientists plan to use the facility to test technology in prolonged low-gravity environments before it's sent to the Moon, where gravity is just one-sixth of its strength on Earth. This will allow them to iron out any costly technical kinks, test whether certain structures will survive on the Moon's surface and assess the viability of a human settlement there.

"Some experiments, such as an impact test, need just a few seconds [in the simulator]," Li said. "But others, such as creep testing, can take several days." A creep test measures how much a material will deform under a constant temperature and stress.

According to the researchers, the inspiration for the chamber came from Andre Geim, a physicist at the University of Manchester in the UK, who won the satirical Ig Nobel Prize in 2000 for devising an experiment that made a frog float with a magnet. The levitation trick used by Geim – and now in the artificial Moon chamber – comes from an effect called diamagnetic levitation. Atoms are made up of atomic nuclei and tiny electrons that orbit them in little loops of current, and these moving currents induce tiny magnetic fields. Usually, the randomly oriented magnetic fields of all the atoms in an object, whether they belong to a drop of water or a frog, cancel out, and no material-wide magnetism manifests.

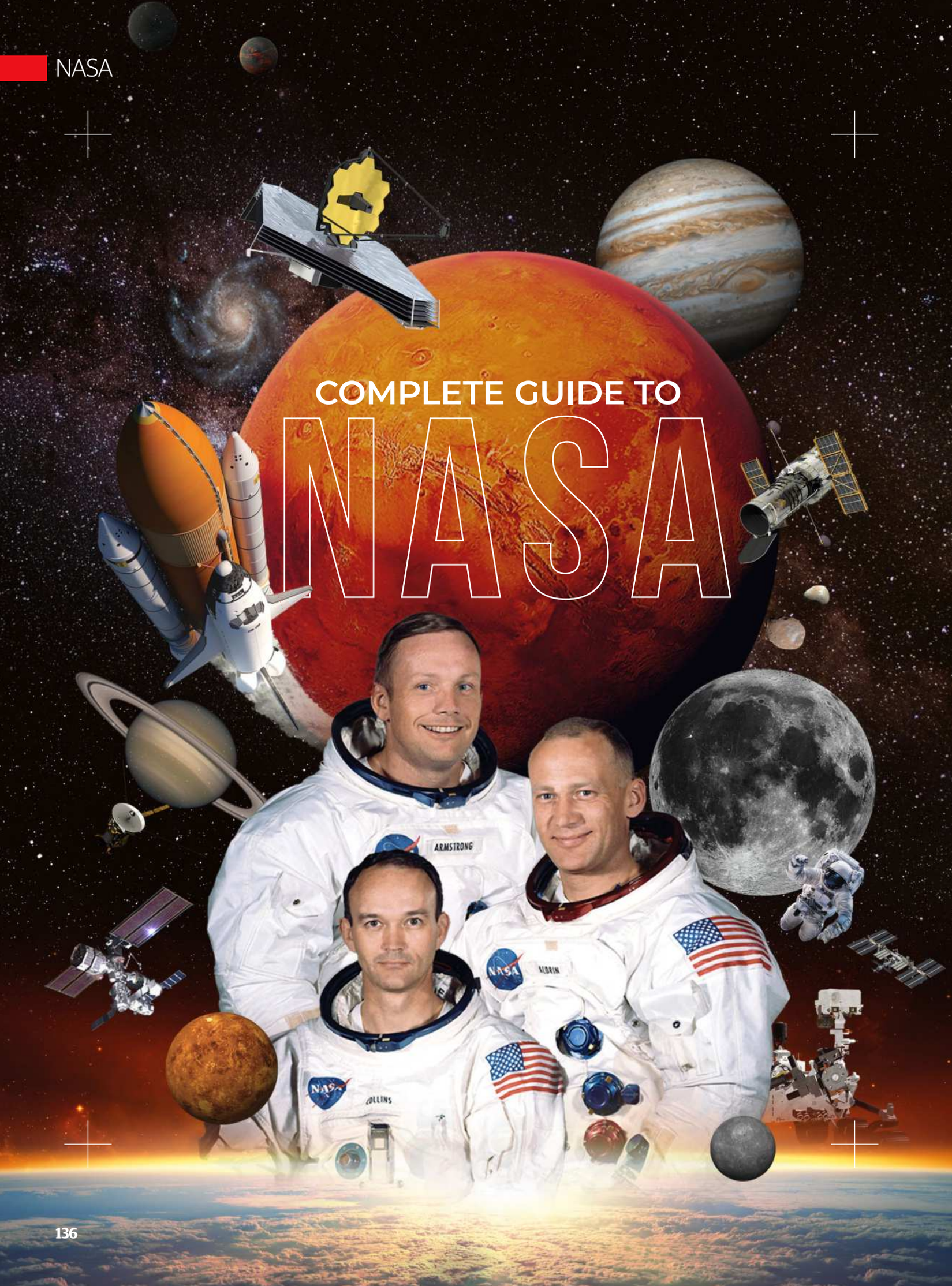
Apply an external magnetic field to those atoms, however, and everything changes: the electrons will modify their motion, producing their own magnetic field to oppose the applied field. If the external magnet is strong enough, the magnetic force of repulsion between it and the field of the atoms will grow powerful enough to overcome gravity and levitate the object – whether it's an advanced piece of lunar tech or a confused amphibian – into the air.

The tests completed in the chamber will be used to inform China's lunar exploration program Chang'e, which takes its name from the Chinese goddess of the Moon. This initiative includes Chang'e 4, which landed a rover on the far side of the Moon in 2019, and Chang'e 5, which retrieved rock samples from the Moon's surface in 2020. China has also declared that it will establish a lunar research station on the Moon's south pole by 2029.



"SCIENTISTS PLAN TO USE THE FACILITY TO TEST TECHNOLOGY IN PROLONGED LOW-GRAVITY ENVIRONMENTS BEFORE IT'S SENT TO THE MOON"

©Getty


COMPLETE GUIDE TO
NASA
ARMSTRONG
NASA
COLLINS

IT'S AN ORGANISATION KNOWN THE WORLD OVER, WITH ITS AMBITIOUS GOALS INSPIRING OTHERS TO DREAM OF TRAVELLING AMONG THE STARS. HERE'S YOUR DEFINITIVE GUIDE TO THE HISTORY OF NASA

Written by Colin Stuart

1950s

The National Aeronautics and Space Administration was founded on 29 July 1958 when President Eisenhower signed the National Aeronautics and Space Act. It was a direct response to the launch of the world's first satellite, Sputnik 1, by the Soviet Union on 4 October 1957. "It is of great urgency and importance to our country, both from consideration of our prestige as a nation as well as military necessity, that this challenge be met by an energetic program of research and development for the conquest of space," read a report from January 1958. NASA was established to do just that.

Attention quickly turned to human spaceflight with the commencement of Project Mercury. Seven potential astronauts, known as the 'Mercury Seven', were selected from a pool of US test pilots. Candidates had to be between 25 and 40 years old, and no taller than 5 feet 11 inches (1.8 metres). Their identities were announced to the world on 9 April 1959. A group of female candidates, now known as the 'Mercury 13', were not included.



© NASA



APOLLO

Probably the most famous NASA program of all time, this ambitious series of missions culminated in 12 moonwalkers visiting our lunar neighbour, performing experiments and collecting Moon material for study back on Earth.

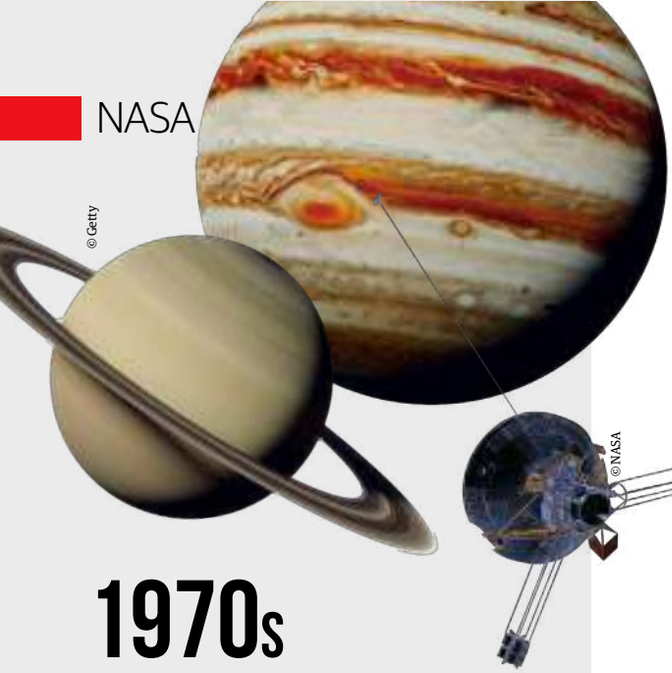
© NASA

1960s

NASA was pipped to the post again when Soviet cosmonaut Yuri Gagarin became the first human in space on 12 April 1961, completing one orbit of the planet. On 5 May the same year, Alan Shepard became the first American in space when he undertook a 15-minute suborbital flight aboard the Freedom 7 spacecraft. Three weeks later, President John F. Kennedy took things up a gear by setting the ambitious goal of landing astronauts on the Moon by the end of the decade.

After testing spaceflight capabilities with the Gemini program, NASA started its fabled Apollo program to meet Kennedy's target. After much planning, Apollo 8 and Apollo 10 saw astronauts fly around the Moon for the first time. Then, on 20 July 1969, Neil Armstrong and Buzz Aldrin set foot on the lunar surface. An estimated 650 million viewers watched worldwide – about one out of every six people on the planet. At last NASA had a significant Space Race victory over the Soviet Union. Two more moonwalkers, Pete Conrad and Alan Bean, left their footprints in the lunar dust before the decade was out as part of the Apollo 12 mission.

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© Getty

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1970s

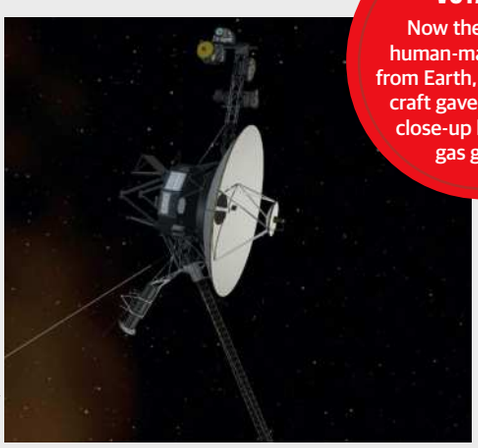
There were four more successful Moon landings in the 1970s, but the decade was just as notable for advances in robotic space exploration. It was the decade of getting to know our neighbouring planets. In 1973 the NASA spacecraft Pioneer 11 flew by both Jupiter and Saturn, while the same year saw Mariner 10 whizz past Mercury and Venus. The twin Viking 1 and Viking 2 landers touched down on the surface of Mars in 1976, sending back NASA's first in-situ pictures of the Martian terrain. Experiments on board initially detected signs of life, but this was later established as a false positive.

In 1977, Voyager 1 and Voyager 2 were lofted into the Solar System to explore the realm of the gas planets beyond the asteroid belt. They both arrived at Jupiter before the decade was out, sending back over 52,000 images of the Solar System's largest planet. The biggest surprise was that Jupiter's moon Io is volcanically active and spewing plumes of material hundreds of metres into space.

"IT WAS THE DECADE OF GETTING TO KNOW OUR NEIGHBOURING PLANETS"

VOYAGER

Now the farthest human-made objects from Earth, the Voyager craft gave us the first close-up look at the gas giants.


© NASA/JPL



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SPACE SHUTTLE

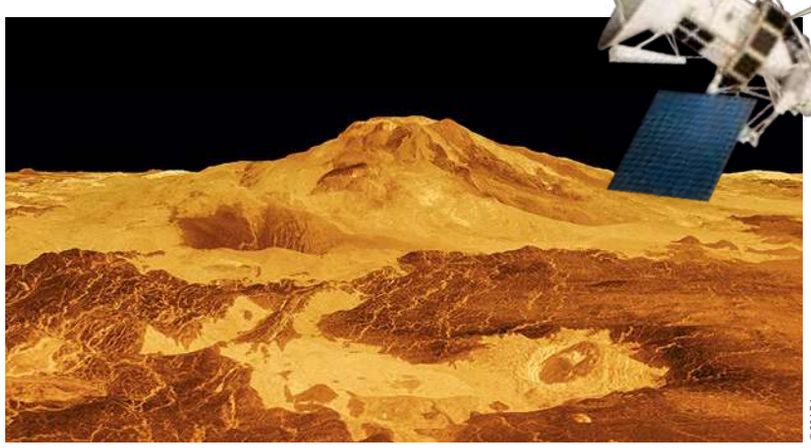
These iconic reusable spacecraft flew a total of 135 missions. There were six different shuttles in service: Enterprise, Columbia, Challenger, Discovery, Atlantis and Endeavour.

© NASA

1980s

This was the first decade of NASA's iconic Space Shuttle. Four fully operational orbiters were initially built. Columbia was the first into space on 12 April 1981 – the 20th anniversary of Gagarin's maiden spaceflight. One of the shuttles' key attributes was their reusability. After launching attached to a distinctive orange fuel tank, the shuttles glided back to Earth after each mission to be used again in the future. But disaster struck in 1986, when Challenger exploded 73 seconds after launch. All seven crew members were lost. The accident grounded the shuttle fleet for more than two-and-a-half years, and the Endeavour shuttle was built to replace Challenger. An investigation concluded that a faulty seal allowed pressurised gas to burn through one of the external fuel tanks. While all this was going on, Voyager 2 reached Saturn in 1981, Uranus in 1986 and Neptune in 1989. It remains the only probe to have visited the two outer planets. The final year of the decade also saw NASA's Magellan probe orbit Venus and the Galileo spacecraft visit Jupiter.


© NASA/JPL


© NASA

Right: We have very few images from Venus' hostile surface as spacecraft don't survive there long



1990s

In April 1990, NASA finally launched the Hubble Space Telescope after a myriad of delays brought on by the Challenger disaster. It was supposed to revolutionise our ability to look deep into space, but mission scientists quickly realised there was a defect with the telescope's mirror – it had been misaligned by an amount equivalent to just 1/50th the width of a human hair.

It took until 1993 to correct the error, when astronauts flew up on the Space Shuttle Endeavour to retrofit a solution called the Corrective Optics Space Telescope Axial Replacement (COSTAR). About the size of a telephone booth, it's the equivalent of a pair of glasses to restore the telescope's ailing vision.

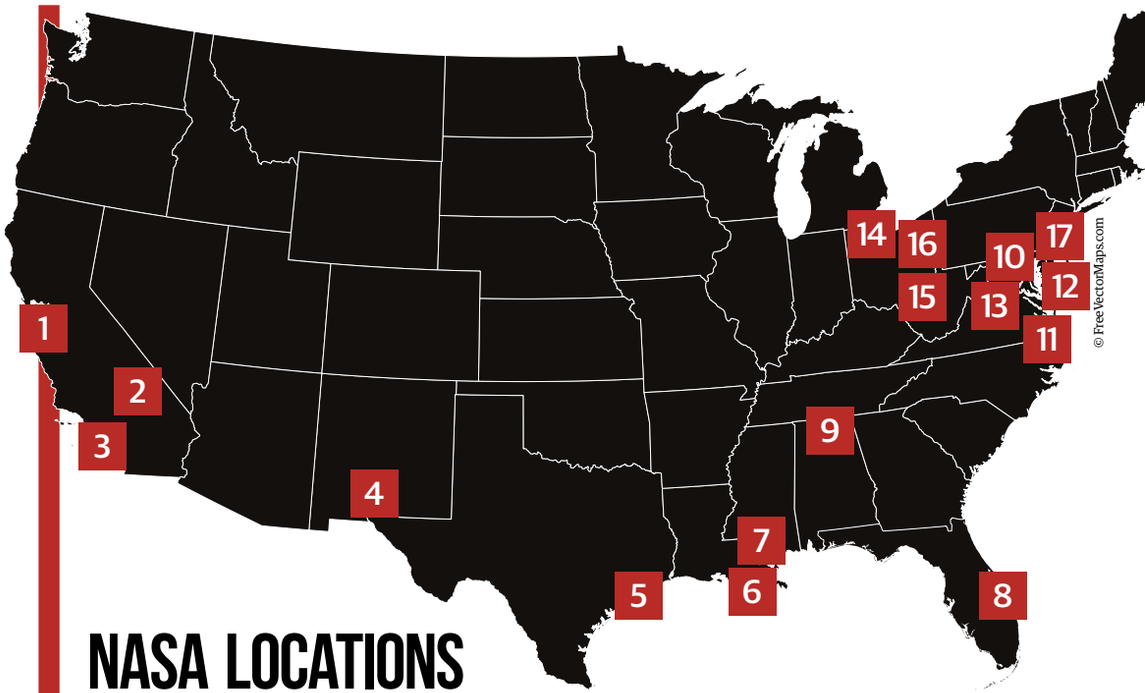
Ulysses, a spacecraft sent to study the Sun's more extreme latitudes, launched on the Space Shuttle Discovery six months after Hubble. Later in the decade, on 4 July 1997, NASA landed Pathfinder on Mars. It was carrying Sojourner, the first-ever Mars rover. Slow Sojourner took three months to trundle just 100 metres (328 feet) through the Martian dust, analysing rocks as it went.

HUBBLE

Supplying scientists with 30 years of data – and wowing us with its images – Hubble has made many breakthroughs possible.



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NASA LOCATIONS

NASA has sites all across the US, though they carry out many different types of research

AMES RESEARCH CENTER

1 Located in the heart of California's Silicon Valley, Ames provides leadership in areas including astrobiology and robotic lunar exploration.

WHITE SANDS TEST FACILITY

4 Set in the western foothills of the Organ Mountains of New Mexico, White Sands is where NASA tests its rocket engines and boosters.

STENNIS SPACE CENTER

7 America's largest rocket engine test facility, it's located on the banks of the Pearl River on the Mississippi–Louisiana border.

MARY W. JACKSON NASA HQ

10 Named after one of the black female scientists depicted in the film *Hidden Figures*, it's the administration centre of NASA in the US capital.

GODDARD SPACE FLIGHT CENTER

13 Spacecraft, instruments and new technology to study Earth, the Sun, our Solar System and the universe are built here.

GLENN RESEARCH CENTER

16 This facility in Cleveland, Ohio, designs and develops innovative technology to advance NASA's missions in aeronautics and space exploration.

ARMSTRONG FLIGHT RESEARCH CENTER

2 Located inside Edwards Air Force Base in California, this is NASA's main location for aeronautical research.

JOHNSON SPACE CENTER

5 The Johnson Space Center in Houston, Texas, is NASA's centre for human spaceflight, including astronaut training and Mission Control.

KENNEDY SPACE CENTER

8 The launch site of the Apollo missions to the Moon, as well as the Space Shuttle. It was named after the president.

LANGLEY RESEARCH CENTER

11 This base is home to more than 40 wind tunnels, which are used to study craft safety and efficiency.

NEIL A. ARMSTRONG TEST FACILITY

14 Home to several world-class test facilities which perform complex and innovative ground tests for the space community.

GODDARD INSTITUTE FOR SPACE STUDIES

17 Conducts theoretical and experimental research in astrophysics, planetary atmospheres and climate studies.

JET PROPULSION LABORATORY

3 The JPL predates NASA and is famous for constructing robotic spacecraft, including all of NASA's Mars rovers.

MICHOUD ASSEMBLY FACILITY

6 One of the largest manufacturing plants in the world, parts of the famous Saturn V rocket were built here.

MARSHALL SPACE FLIGHT CENTER

9 The largest NASA centre, it's the US government's civilian rocketry and spacecraft propulsion research base.

WALLOPS FLIGHT FACILITY

12 Located on Wallops Island, the technology tested at Wallops includes sounding rockets and high-altitude balloons for astronomical research.

KATHERINE JOHNSON INDEPENDENT VERIFICATION AND VALIDATION FACILITY

15 Named after another 'hidden figure', the software for NASA's space missions is put through its paces here.

STANDOUT MOMENTS IN NASA HISTORY

29 JULY 1958
National Aeronautics and Space Administration was founded

President Eisenhower signed the National Aeronautics and Space Act in response to Sputnik.

5 MAY 1961
Alan Shepard became the first NASA astronaut

He spent 15 minutes in space on a suborbital flight.

20 JULY 1969
First crewed Moon landing

Neil Armstrong and Buzz Aldrin made history as the first moonwalkers.

12 APRIL 1981
First Space Shuttle launched

The first Space Shuttle to leave Earth was the ill-fated Columbia.

28 JANUARY 1986
Challenger exploded just after launch

The death of seven crew members saw the fleet grounded for more than two years.

2 NOVEMBER 2000
The first crew visited the International Space Station

It was the beginning of staying in space for months rather than days at a time.

1 FEBRUARY 2003
Columbia broke up on re-entry

A second catastrophic disaster befell the Space Shuttle, resulting in the loss of the entire crew.

31 AUGUST 2011
The formal end of the Space Shuttle program

The Space Shuttle was retired after Atlantis made the 135th and final flight in July 2011.

9 DECEMBER 2020
Artemis lunar mission crew announced

18 astronauts were selected for Artemis Team, from which the next moonwalkers will be picked.



INTERNATIONAL SPACE STATION

Assembled in segments over the course of over ten years and 30 missions, the ISS is a collaboration between NASA, the European Space Agency, Roscosmos, the Japan Aerospace Exploration Agency and the Canadian Space Agency.

2000s

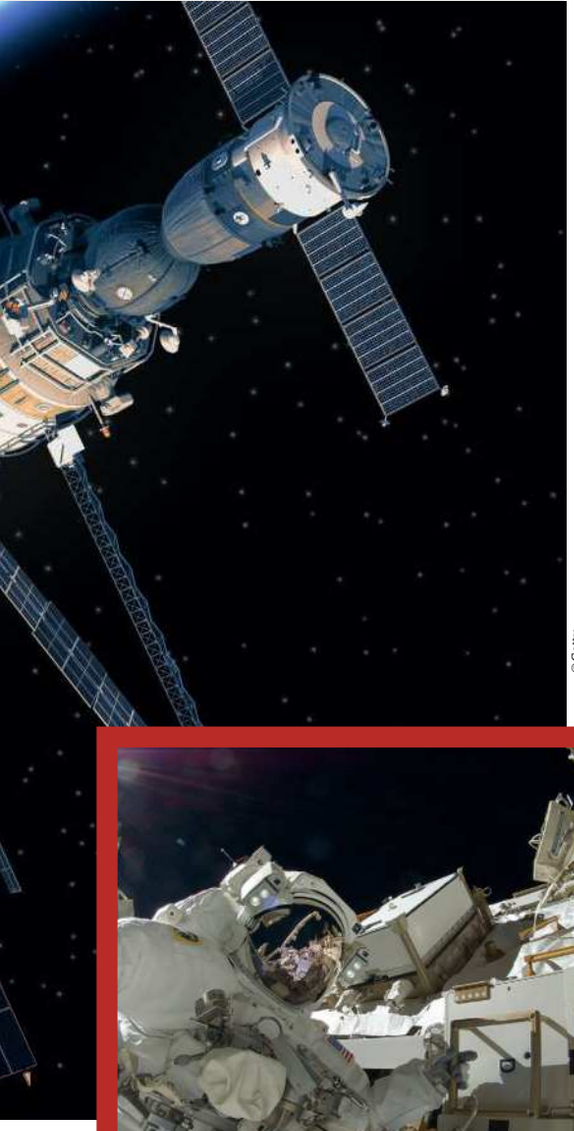
The newly constructed International Space Station (ISS) got its first crew. It quickly became an ideal orbital outpost on which we could learn more about long-duration human spaceflight. To this day, more NASA astronauts have flown to the ISS than any other nation's space travellers. A second disaster occurred when Columbia broke up on re-entry in 2003, killing all seven of the crew.

Planetary exploration was dominated by Saturn and Mars. NASA's Cassini probe arrived at the ringed planet in 2004 and began sending back jaw-dropping images of the planet, its rings and its moons. That same year the twin Spirit and Opportunity rovers landed on Mars, returning stunning pictures of Martian sunsets and Earth hanging in the Martian sky. Spirit eked out an existence until getting stuck in the mud in 2010. Remarkably, Opportunity lasted until 2019, despite the fact it was only designed to work for 90 days. NASA also got to know the Moon even better thanks to the Lunar Reconnaissance Orbiter (LRO), which launched in 2009. It returned images of the Apollo 11 landing site, including the Eagle lander glinting in the sunlight.



Below: All seven of Columbia's crew were lost upon re-entry

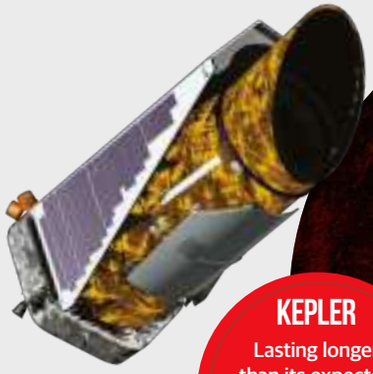
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Below: Curiosity has been exploring Gale crater, which may be an ancient lake

© NASA



KEPLER

Lasting longer than its expected mission time, Kepler truly revolutionised exoplanet research.

2010s

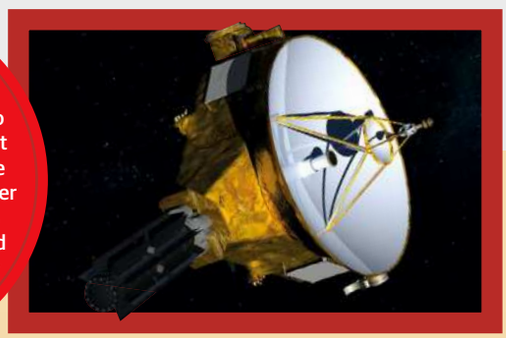
We began to get deeper answers to the question of whether we're alone in the universe thanks to NASA's Kepler space telescope. Launched in 2009, it took until January 2011 to announce the discovery of its first rocky planet beyond our Solar System. What it went on to discover revolutionised our understanding of what's possible when it comes to alien planets. It found exoplanets orbiting their stars in mere hours, others that have two suns instead of one and yet others where the temperature appears to be right to permit the presence of liquid water.

A year after the last Space Shuttle launch in 2011, NASA attempted its most audacious Mars landing yet. The Curiosity rover, currently still hard at work on the Red Planet, is almost double the dimensions of Spirit and Opportunity. Those missions had been deployed using an inflatable cocoon that bounced and deflated to allow the rovers to drive out. Curiosity was too big for that, so it was lowered onto the Martian surface using a futuristic-looking sky crane.

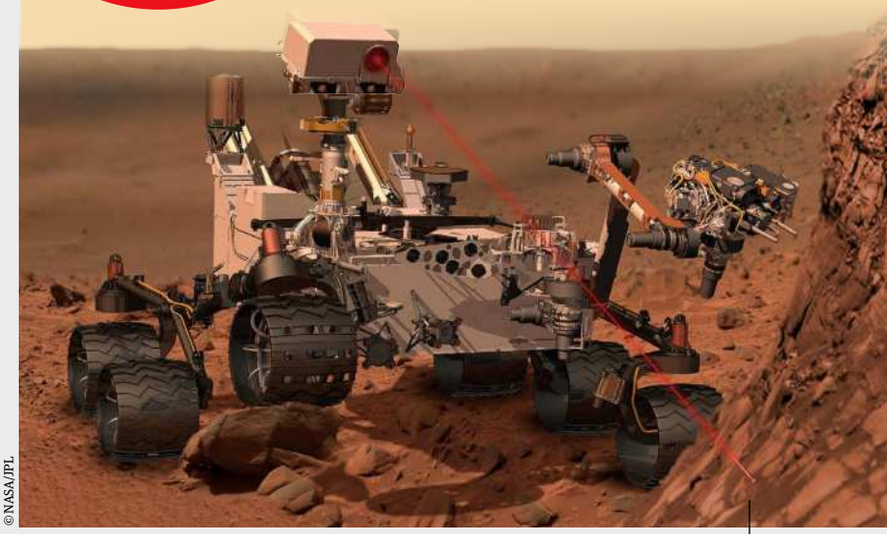
New Horizons reached the dwarf planet Pluto in 2015 after a nine-year voyage out to the region beyond the planets. The vivid images it sent back revealed a surprisingly active world for an object marooned so far from the warmth of the Sun. Curiosity was joined on Mars by the InSight lander in 2018, which is designed to look for marsquakes and probe the Red Planet's inner structure.

NEW HORIZONS

Seven months after the launch of New Horizons, Pluto was demoted to a dwarf planet after similar small bodies were discovered and reclassified. After snapping Pluto's 'heart' on its flyby, the spacecraft continued on to the Kuiper Belt to study 486958 Arrokoth.



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IMPORTANT PEOPLE AT NASA

BILL NELSON

Administrator



Nelson served in the US Senate and flew on Space Shuttle mission 61-C in 1986.

"Are we alone? Personally, I don't think we are."

PAMELA MELROY

Deputy administrator



One of only two women to command a Space Shuttle, Melroy spent 38 days and 20 hours in space.

"There'll be excitement, fulfilment, boredom and routine, and even the occasional train wreck."

KATHY LUEDERS

Associate administrator of human exploration and operations



The first female head of human spaceflight, Lueders was appointed to the role in June 2020.

"It's exciting to see us maximising the ISS and expanding access to low-Earth orbit."

x3 Images © NASA



2020s

Martian exploration continues at pace, including dispatching Ingenuity – a helicopter that performed the first powered flight on Mars – from the Perseverance rover on 19 April 2021. We could soon know more about deflecting hazardous asteroids, too. In November 2021, NASA launched its Double Asteroid Redirection Test (DART). By the end of 2022 it will have hopefully collided with the asteroid Dimorphos, nudging it slightly off course.

Hubble's long-awaited successor, the James Webb Space Telescope (JWST), made it into space on 25 December 2021 after decades of wrangling, political setbacks and engineering delays. The unfurling of its sunshield went perfectly, as did the unfolding of its huge mirror. Arriving at its destination in January 2022, it will look back in time to the formation of the first stars and galaxies. NASA is also gearing up for its astronauts to return to the Moon for the first time since 1972. Its Artemis program is set to put the first female astronaut and first astronaut of colour on the Moon in 2025.

NASA has been around for more than six decades and continues to set the benchmark for space exploration. Yet it has faced numerous challenges throughout its long history. It has persisted through the administrations of no fewer than 13 US presidents, each with their own agendas, goals and manifestos.

Now, in the 21st century, it's repositioning itself to work alongside the growing number of private space companies and enterprises, like SpaceX. Given that NASA is ultimately taxpayer funded, it increasingly needs to justify its existence and look for value of money. It also needs to make the case for continued space exploration in the middle of an ongoing climate emergency. The next decade could be as crucial as the last six in terms of NASA's place in the world and beyond.

Above: Webb will view the ancient universe using its infrared eyesight

ARTEMIS

With the aim of putting the first woman and first person of colour on the Moon by 2025, the Artemis program has been in development and testing for a while now. The first crewless mission should fly in the next few months if all goes to plan.



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NASA'S TOP MISSIONS

NASA has explored every known planet in our Solar System



CASSINI

Launch date: 15 October 1997

End date: 15 September 2017

Description: The first probe to enter Saturn orbit, it dispatched a lander to Titan called Huygens.

VOYAGER 2

Launch date: 20 August 1977

End date: Ongoing

Description: The only probe to visit Uranus and Neptune.





DAWN

Launch date: 27 September 2007

End date: 30 October 2018

Description: The first probe to orbit two extraterrestrial objects, asteroids Ceres and Vesta.



NEW HORIZONS

Launch date: 19 January 2006

End date: Ongoing

Description: The first probe to visit Pluto, it continues to explore the Kuiper Belt.

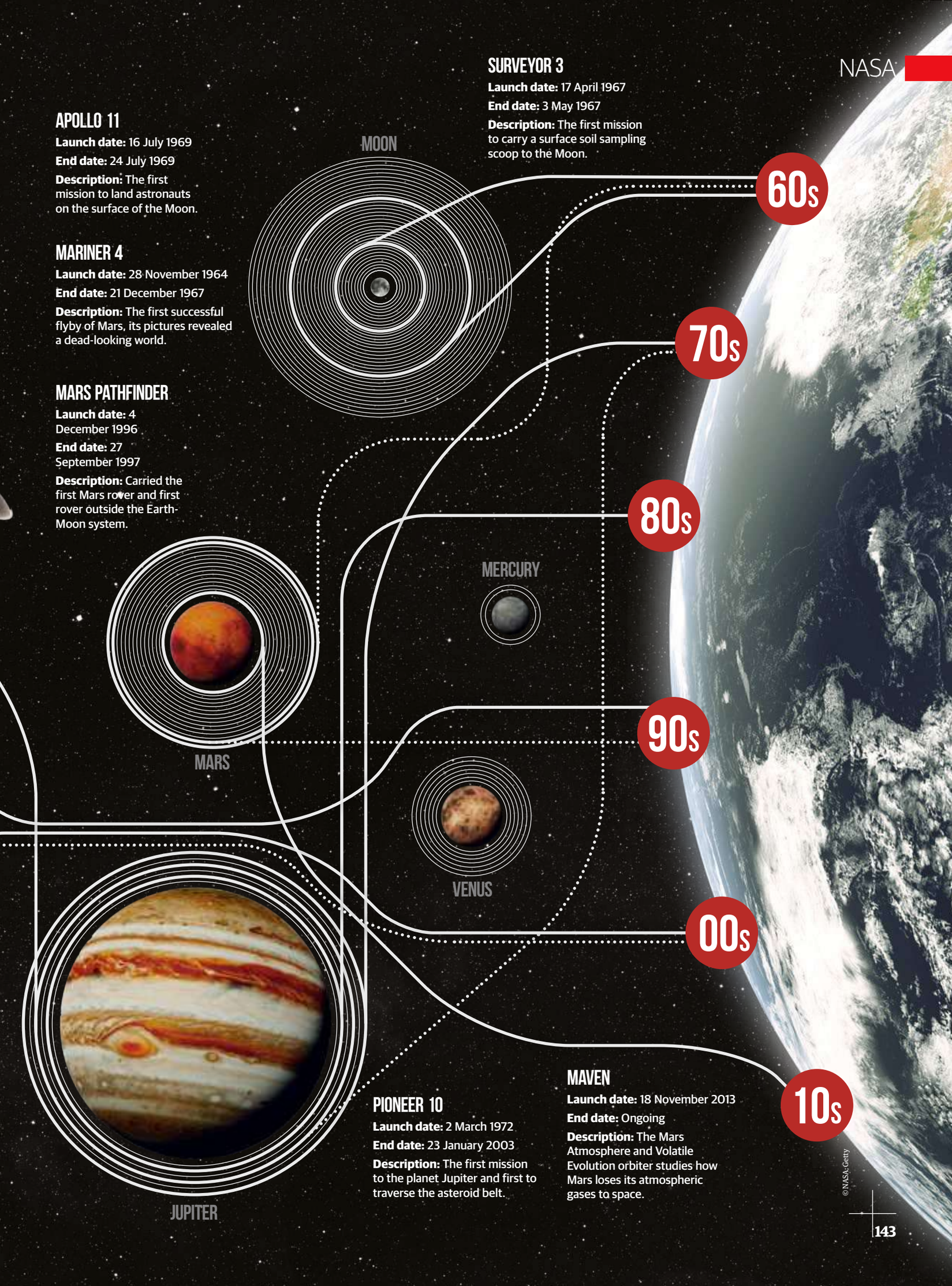


GALILEO

Launch date: 18 October 1989

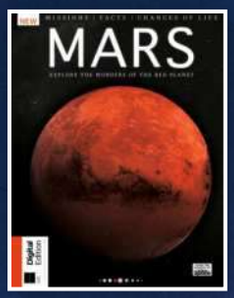
End date: 21 September 2003

Description: The probe studied Jupiter and its moons and the asteroids Gaspra and Ida.


NASA
APOLLO 11
Launch date: 16 July 1969
End date: 24 July 1969
Description: The first mission to land astronauts on the surface of the Moon.
MARINER 4
Launch date: 28 November 1964
End date: 21 December 1967
Description: The first successful flyby of Mars, its pictures revealed a dead-looking world.
MARS PATHFINDER
Launch date: 4 December 1996
End date: 27 September 1997
Description: Carried the first Mars rover and first rover outside the Earth-Moon system.
SURVEYOR 3
Launch date: 17 April 1967
End date: 3 May 1967
Description: The first mission to carry a surface soil sampling scoop to the Moon.
MOON
60s
70s
80s
MERCURY
90s
MARS
VENUS
00s
JUPITER
PIONEER 10
Launch date: 2 March 1972
End date: 23 January 2003
Description: The first mission to the planet Jupiter and first to traverse the asteroid belt.
MAVEN
Launch date: 18 November 2013
End date: Ongoing
Description: The Mars Atmosphere and Volatile Evolution orbiter studies how Mars loses its atmospheric gases to space.
10s
©NASA; Getty



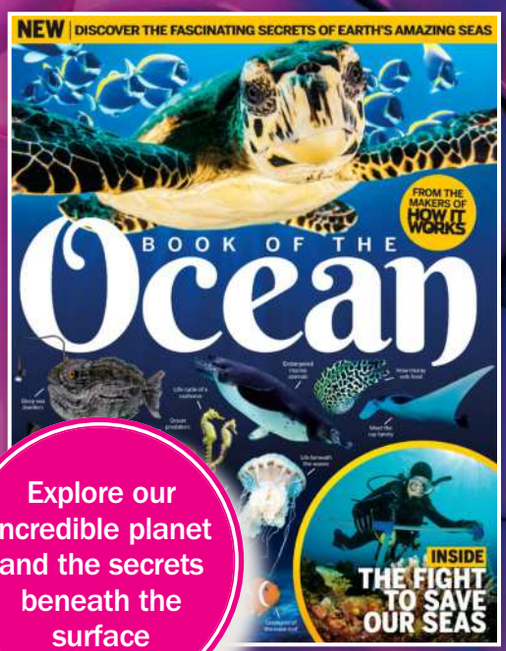
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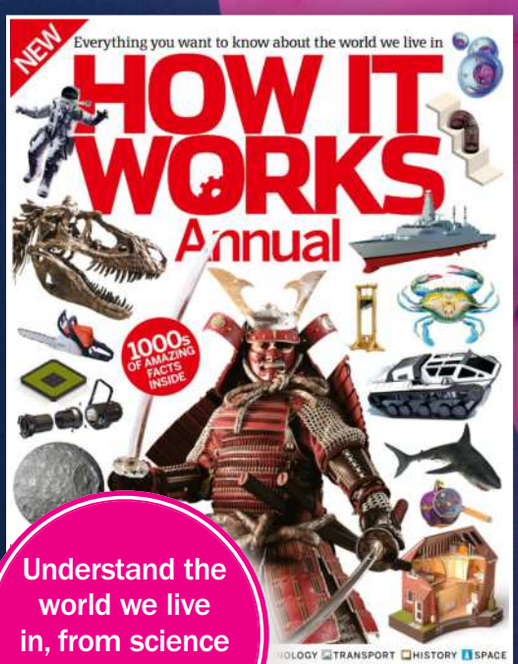
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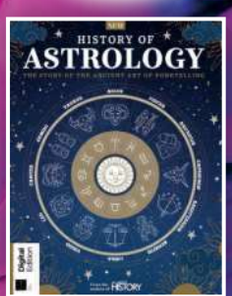








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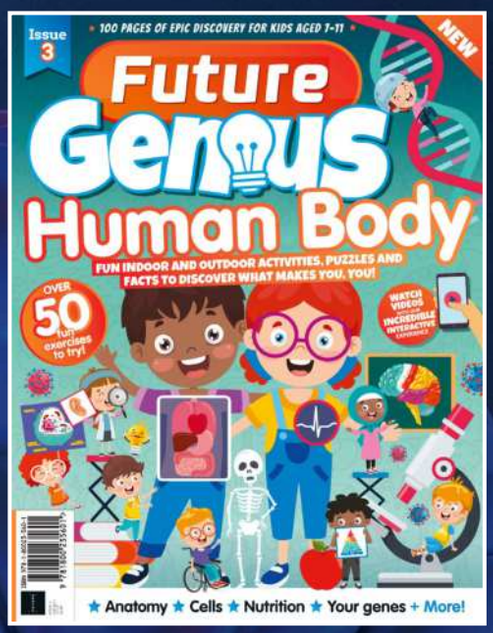


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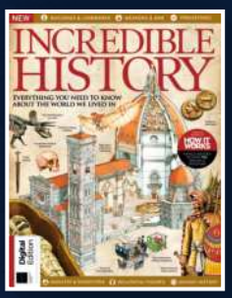
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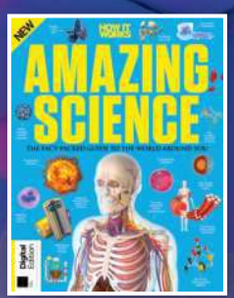






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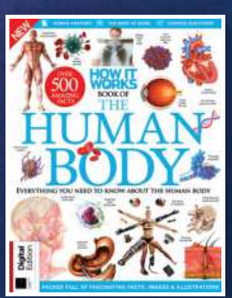












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